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High Performance Arcjet Engines

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HIGH PERFORMANCE

ARCJET ENGINES

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I. PROJECT SUMMARY.

This effort sought to exploit advanced single crystal tungsten-tantalum alloy material for fabrication of a high strength, high temperature arcjet anode. The use of this material is expected to result in improved strength, temperature resistance and lifetime compared to state of the art polycrystalline alloys.

In addition, the use of high electrical and thermal conductivity carbon-carbon composites was considered, and is believed to be a feasible approach. Highly conductive carbon-carbon composite anode capability represents enabling technology for rotating-arc designs derived from the Russian Scientific Research Institute of Thermal Processes (NIITP) because of high heat fluxes at the anode surface. However, for US designs the anode heat flux is much smaller, and thus the benefits are not as great as in the case of NIITP-derived designs. Still, it does appear that the tensile properties of carbon-carbon can be even better than those of single crystal tungsten alloys, especially when nearly-single-crystal fibers such as Vapor Grown Carbon Fiber (VGCF) are used. Composites fabricated from such materials must be coated with a refractory carbide coating in order to ensure compatibility with high temperature hydrogen.

Fabrication of tungsten alloy single crystals in the sizes required for fabrication of an arcjet anode has been shown to be feasible. Test data indicate that the material can be expected to be at least the equal of W-Re-HfC polycrystalline alloy in terms of its tensile properties, and possibly superior.

We are also informed by our colleagues at Scientific Production Association Luch (NPO Luch) that it is possible to use Russian technology to fabricate polycrystalline W-Re-HfC or other high strength alloys if desired. This is important because existing engines must rely on previously accumulated stocks of these materials, and a fabrication capability for future requirements is not assured.

II. INTRODUCTION AND OVERVIEW

Perspectives from the Scientific Research Institute of Thermal Processes (NIITP) indicate that arcjet thrusters are of special interest among electric propulsion engines because they are perceived to be a credible near-term method to achieve high specific impulse propulsion systems. NIITP perspectives are summarized in reference 1 and are updated here.

Having smaller specific impulse (I_{sp}) than electromagnetic and ion thrusters, arcjets provide a rather high absolute thrust level. For this reason arcjet thrusters are particularly attractive for solving a number of space technology problems, especially for such applications as orbit transfer of spacecraft having electric power sources.

Among their deficiencies are limited specific impulse, which is mainly due to the thermodynamic nonequilibrium nozzle exhaust and thruster limited lifetime related to electrode erosion and distortion in the arc discharge region.

The majority of efforts on advanced arcjets are focused on thrusters of low to moderate power (less than 80 kW). Although the arcjet itself scales favorably to even higher power levels, this is perceived to be not necessary in view of the status of power supply technology. Even with the advent of thermionic nuclear power systems, it is likely that most satellites will be limited to several kilowatts, at least for the next several years. This is adequate for applications such as drag makeup, attitude correction and maneuvering.

Accordingly, it is reasonable to assume that few-kilowatt or lower arcjets based on working fluids such as hydrazine or ammonia, are likely to represent the state of the art for the near term.

Future development efforts may emphasize higher performance working fluids such as liquid hydrogen. For the very far term, it is possible to consider megawatt-level electric propulsion devices. Such devices can be tested experimentally, though spacecraft power supply technology limitations prevent their utilization in space at present.

At any rate, as the thruster size is scaled to several megawatts, a reduction of losses relating to nonequilibrium nozzle flow may be expected, as compared to the previously mentioned low power thrusters. Calculated loss reductions can be observed in Figure 2.1. For example, scaling from 30-50 kW to the 5-7 MW level (nozzle length 0.5 m) causes the specific impulse to be augmented by about 160 s, making it possible to obtain 1900 s I_{sp} at the thruster chamber temperature of 6000 K.

Calculations have been made for a thruster chamber temperature of 6000 K and for a thermodynamic equilibrium state at this temperature. One dimensional nozzle reacting gas flow has been calculated. Most of the chemical reaction rate constants for dissociation and recombination were taken from the work of Kondratiev.³ The method of rigid systems of ordinary differential equations offered by Gir has been used, implemented in the program developed at the Institute of Applied Mechanics.⁴

For the problems of interest, thruster specific impulse nears an asymptotic limit when the nozzle outlet to nozzle throat area ratio is more than 500 to 600, for a nozzle length of about 0.5 m. An additional nozzle length increase up to 1.5 m provides further specific impulse augmentation of about 70 s. The same gain can be obtained without nozzle length extension but by changing the nozzle profile so as to provide the initial

supersonic nozzle part with a more smooth profile with smaller temperature and pressure gradients. Potential gains in I_{sp} are shown in Figure 2.1. The results show that a nozzle contour should be specially profiled to provide hydrogen or other propellant recombination reactions.

Specific Impulse, seconds

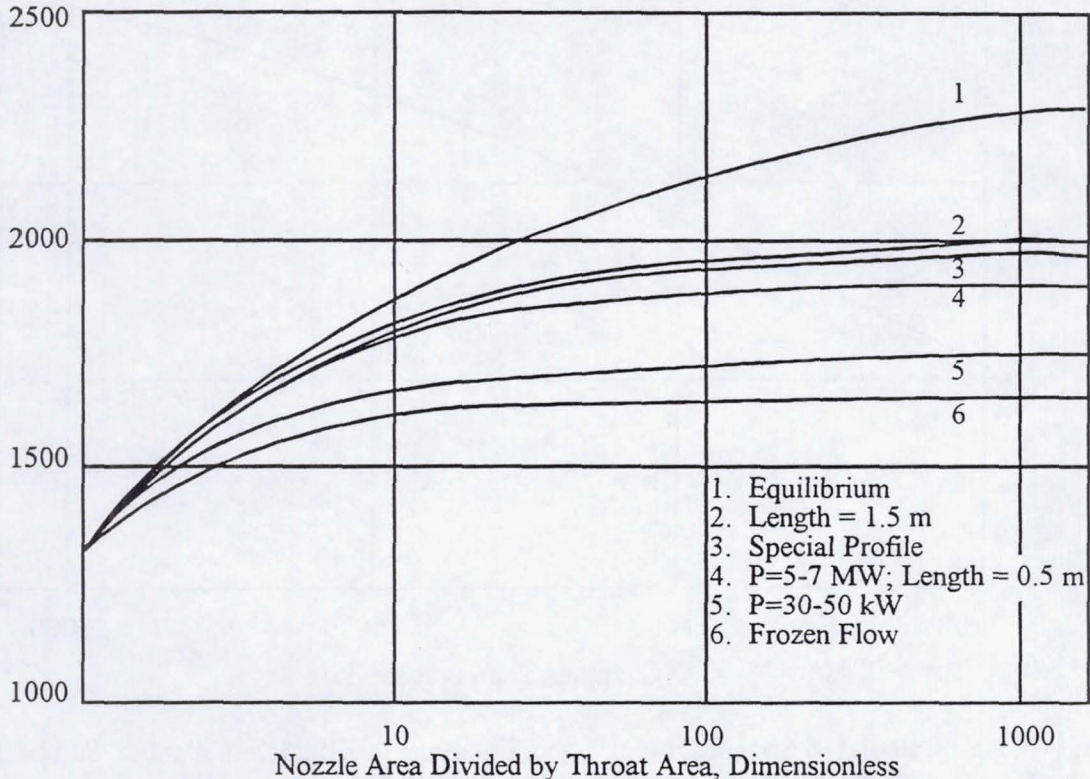
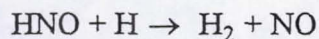
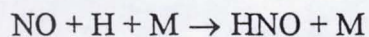


Figure 2.1. Hydrogen Thruster Specific Impulse Versus Nozzle Area Ratio for Various Arcjet Configurations.

The increase of the arcjet thruster chamber temperature results, naturally, in a specific impulse increase (see Figure 2.2). However, the efficiency of conversion of gas enthalpy in the thruster chamber into kinetic energy (thrust efficiency η) is significantly decreased, reaching a value of 0.56 at a chamber temperature of 6000 K (η is the ratio of the nozzle outlet kinetic energy to total gas enthalpy in the thruster chamber). Eschenroeder showed that some thruster specific impulse increase could be achieved with 1% carbon addition to hydrogen at the chamber temperature of 4500 K and at some (purposely increased) values of reaction rate constants.⁵ During a discussion of this work Eugden suggested that probably the reaction



could have a strong catalytic effect.

Preliminary calculations for a chamber temperature of 6000 K, pressure 1 Mpa with 1% N and 1% O₂ addition to hydrogen did not give the expected result. The reactions system and speed constant values used in these calculations were taken from Sheshadri.⁶

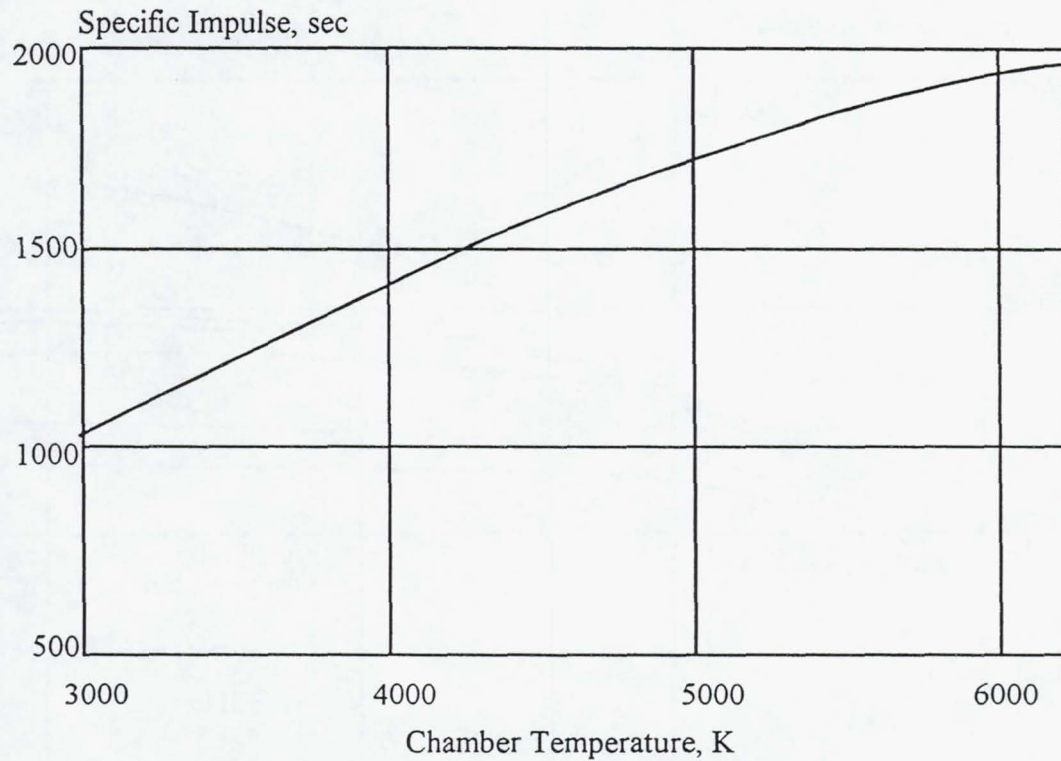


Figure 2.2.a Calculated Specific Impulse as a Function of Effective Chamber Temperature for a Nozzle Area Ratio Between 500 and 600; $P = 1$ MPa.

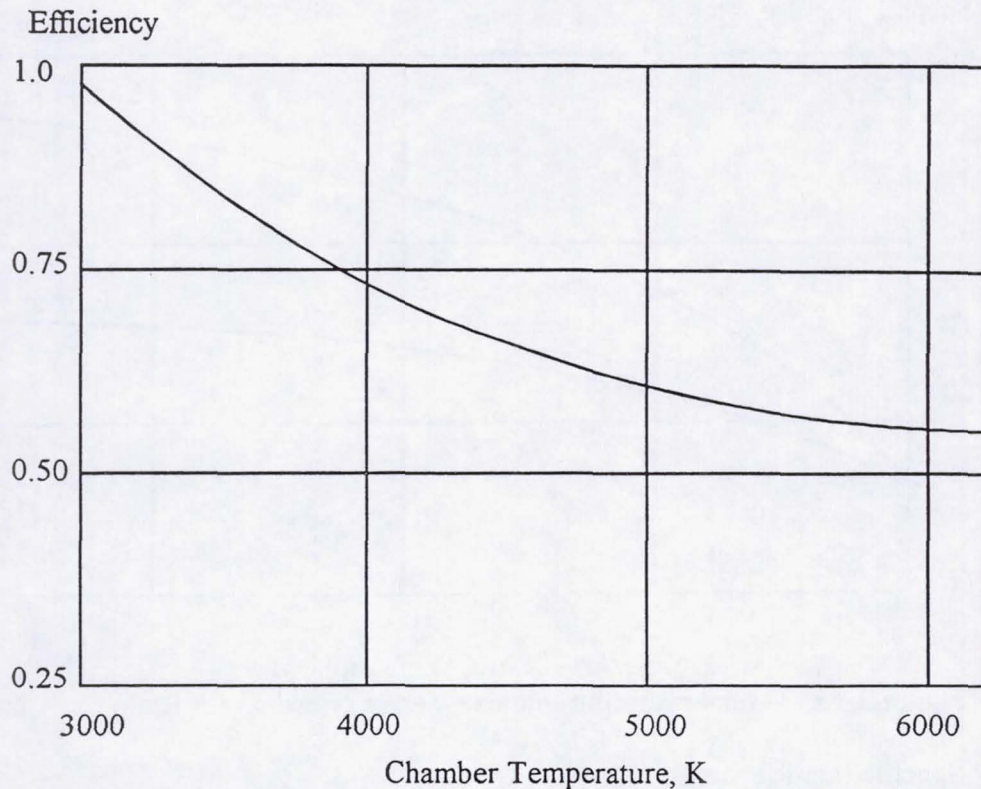


Figure 2.2.b Calculated Efficiency as a Function of Effective Chamber Temperature for a Nozzle Area Ratio Between 500 and 600; $P = 1$ MPa.

The effect of hydrogen recombination via reactions such as $H + H + H \rightarrow H_2 + M$ rate constant should be considered in additional detail. As it has been already mentioned, the value of the reaction rate constants were taken from the work of Kondratiev were used to evaluate the case when the third particle was atomic hydrogen (H).³ Similar results were obtained when using the reaction rate constant of Bashkin.⁷

However, for the case in which the third particle is assumed to be molecular hydrogen, the hydrogen recombination rate constants lead to much smaller specific impulse values: 1700 instead of 1900 seconds (for $T_{\text{chamber}} = 6000$ K). This once again emphasizes the degree of theoretical analysis reliability and the importance of its experimental verification.

Other propellants instead of hydrogen are likewise of interest. In particular ammonia and helium have some good performance qualities. The results of calculations showed (see Figure 2.3) that when employing these gases 800-900 s specific impulse could be expected as the thruster chamber temperature $T = 6000$ K.

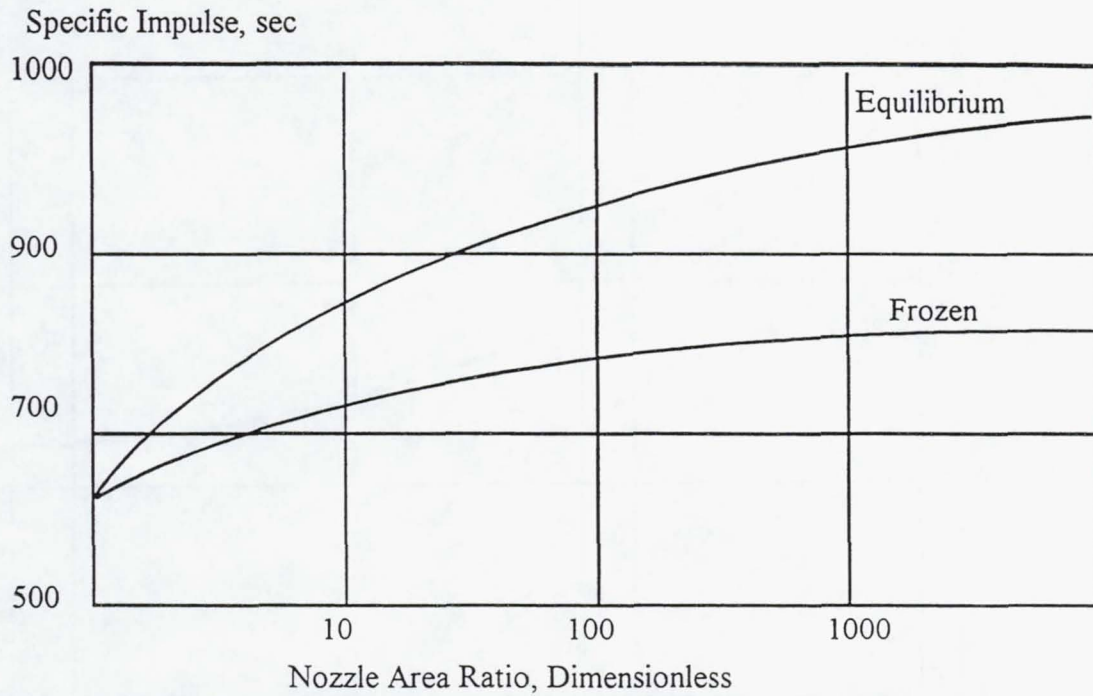


Figure 2.3.a Thruster Specific Impulse Versus Nozzle Area Ratio for Ammonia.

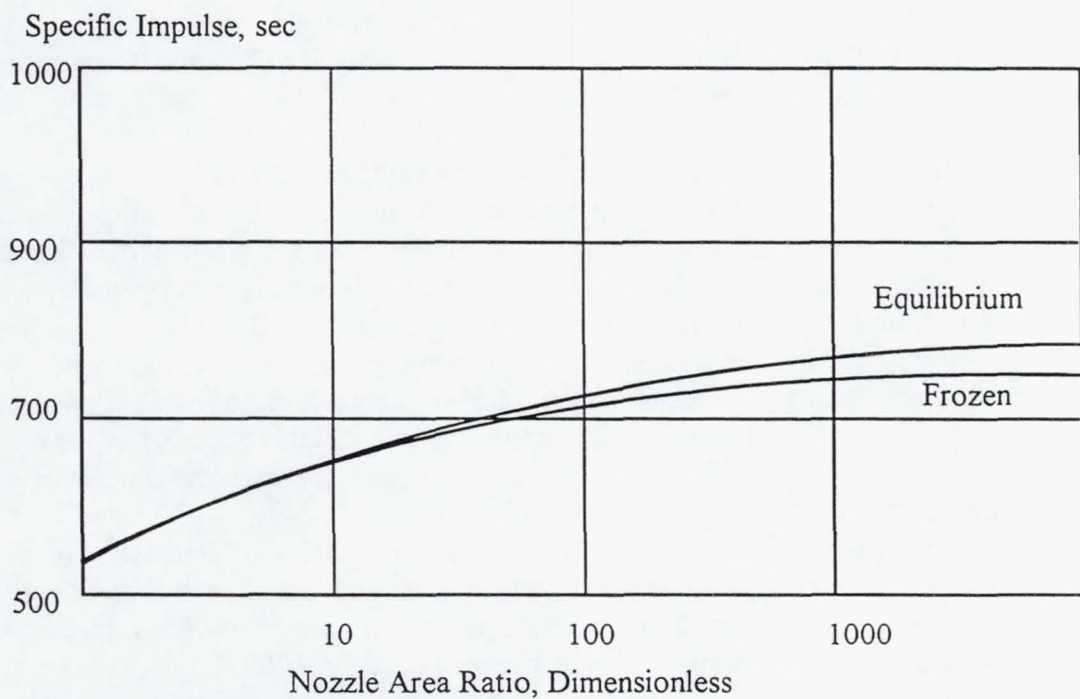


Figure 2.3.b Thruster Specific Impulse Versus Nozzle Area Ratio for Lithium.

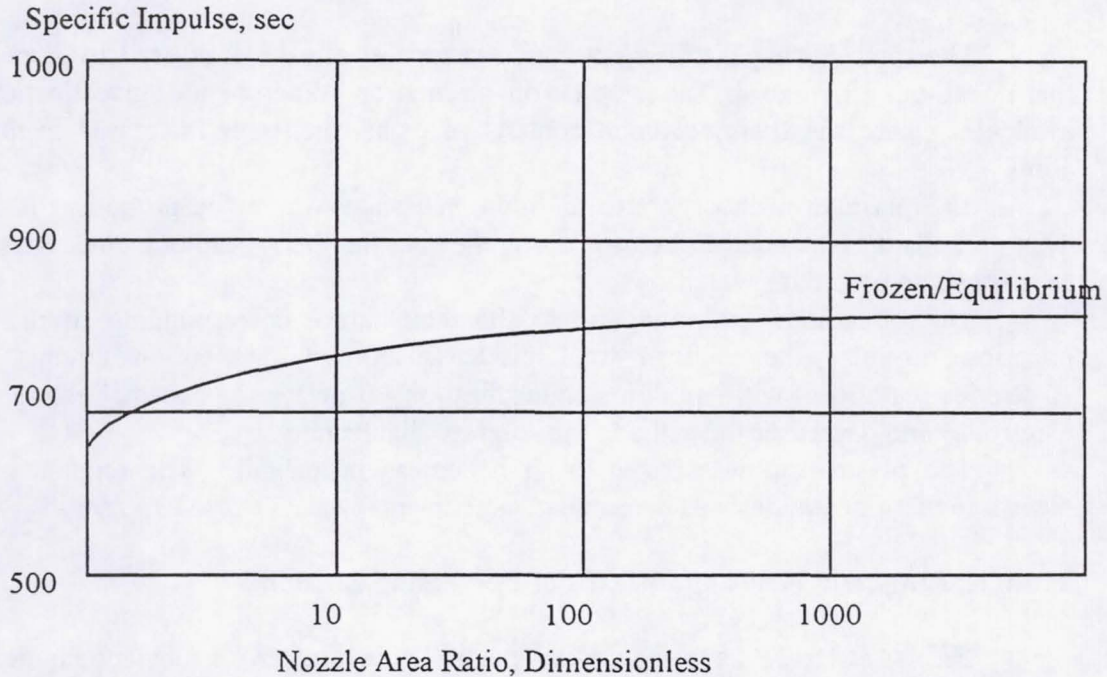


Figure 2.3.c Thruster Specific Impulse Versus Nozzle Area Ratio for Helium.

Electrode Lifetime Issues

As far as electrodes lifetime is concerned, a great deal experience has been gained while working with arcjet plasmatrons, since the working process of discharge chambers of which has much in common with those of arcjet thrusters. In this regard, arcjet plasmatrons have successfully demonstrated satisfactory performance while generating high temperature flows of hydrogen and other propellants.

Pustogarov reported the results of experimental investigations on performance of a coaxial plasmatron with a butt-end cathode fabricated from W-La.⁸ The cathode diameter was 7-100 mm, the anode diameter was 20-74 mm. The magnetic field solenoid induction changed within 0.06 to 0.1 T.

The plasmatron thermocathode lifetime investigation results are given in Table 2.1.

Table 2.1. Plasmatron Cathode Lifetime Results.

Current I kA	Pressure P bar	Cathode dia., d_c , cm	Run time, t , min	Cathode erosion G , g/K
0.2	4	1.0	4	4.2×10^{-6}
0.3	4	1.0	4	3.8×10^{-6}
0.5	4	0.1	4	1.0×10^{-5}
0.7	4	0.1	4	1.1×10^{-5}
0.95	4	0.1	4	6.2×10^{-4}
0.35	1	1.0	4	1.7×10^{-7}
0.35	4	1.0	4	3.8×10^{-6}
0.35	7	1.0	4	1.9×10^{-5}
0.35	13	1.0	4	4.0×10^{-5}

The total current distribution among several electrodes was used to increase the thermocathode lifetime. The results of plasmatron experimental investigations are available, where the thermocathode consists of eight electrodes fabricated from W-La alloy.

The plasmatron incorporates an additional stage where the propellant is heated. This propellant is intended to be used for preheating the thermocathode electrodes of the primary stage before its switch-on.

Thermocathode preheating up to the temperature corresponding to thermionic emission provides the uniform total discharge current distribution among several electrodes (cathodes) with arc diffusion localization. It delays the onset of erosion of the electrodes and decreases the cathode erosion rate significantly.

The plasmatron was tested using helium as propellant. The erosion of eight electrode thermocathodes was determined experimentally as $G = 2 \times 10^{-8} \text{ g/K}$.

Induced Magnetic Fields as a Means of Decreasing Erosion

Efforts at NIITP have shown that electrode erosion can be substantially decreased by applying an induced magnetic field.⁹ This results in a high volt-ampere ratio for the discharge (i.e., the effective plasma resistance is lowered) and hence increases the relative power input to the propellant flow. This in turn makes it possible to obtain high rotation speeds of discharge near the electrode zones and to increase significantly the electrode lifetime due to the rotational zones displacement.

NIITP tests reportedly have shown that erosion could be decreased up to 10^{-7} g/K , and the cathode lifetime could be brought up to 10,000-20,000 hours, which finally indicates the feasibility of creating a new generation of electric thrusters.

In this case, anode lifetime is more of an issue than the cathode lifetime. Of particular importance is minimizing the thermal spiking which occurs as the arc rotates along the surface of the anode.

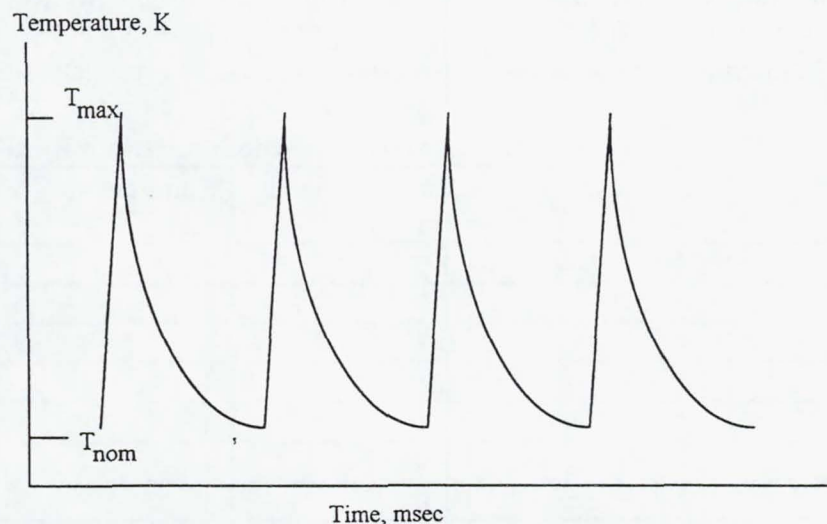


Figure 2.4. Conceptual Illustration of Thermal Cycling Experienced on a Spot on an Arcjet Anode Subjected to a Rotating Arc.

The differential equation describing time variant heat conduction is

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

where T is the temperature (K), x is the spatial coordinate (cm), and thermal diffusivity α is given by

$$\alpha = \frac{k}{\rho c}$$

where in turn k is the thermal conductivity (W/cmK), ρ is the density (g/cm³), and c is the specific heat (J/gK).

Solutions to the time-dependent thermal conduction equation can be obtained using straightforward numerical modeling techniques. The boundary conditions which need to be applied will modeling the heating of the anode via electron bombardment, radiative and convective heat transfer between the anode wall and gas; and so on.

However, it is not necessary to completely solve this equation. The general character of the cooling of the anode will be an exponential function of thermal diffusivity:

$$T = A \exp^{(-B\alpha t)}$$

where A and B are determined by the boundary conditions. The key observation is that the cooling of the anode will be controlled by the thermal diffusivity; the higher the thermal diffusivity, the cooler the anode and the higher the heat flux which can be accommodated.

For this reason, efforts at NIITP have concentrated on copper anodes for this purpose, even though the copper melting point is only 1356 K. At 1000 K, the thermal conductivity of copper is 3.48 W/cmK, density 8.9 g/cm³, and heat capacity of 0.38 J/gK.

Thus the thermal diffusivity of hot copper is equal to 1.03 cm²/sec.

For carbon/carbon composites, the heat capacity is 0.709 W/mK, thermal conductivity of 8 W/cmK and density 2.0 G/cm³, leading to a thermal diffusivity of 5.6 cm²/sec. This is high enough to solve the thermal spiking problem. Moreover, carbon-carbon remains strong at high temperature. The limiting factor will be the effectiveness of refractory carbide coatings in protecting the anode from attack by hydrogen.

US Perspectives on NIITP Concept

In the US and in other western nations over the past ten years, excellent progress has been made on improving cathode lifetime via improved thermal design of the cathode. Lifetimes comparable to or even in excess of the NIITP claims appear to be within the state of the art. Thus, the motivation for adopting a rotating arc design appears to be less obvious, unless additional performance advantages can be indicated. Thus far, the US

community has not been made aware of performance advantages using this approach which can not be obtained through an alternate, less radical approach.

For this reason, emphasis in this effort was shifted towards the consideration of refractory metals for arcjet electrode materials. Single crystal tungsten alloys may be superior to polycrystalline alloys especially as far as the development of a long-lived anode is concerned.

References.

1. A. S. Koroteyev et al., "Arcjet Thrusters," IAF-90-227, 41st IAF Congress, Oct 6-12, Dresden.
2. J. R. Stone and F. S. Huston, "The NASA/USAF Arcjet Research and Technology Program," AIAA Paper 87-1946, 1987.
3. V. S. Kondratiev, *Gas Reaction Rate Constants*, Nauka, Moscow, 1971.
4. A. Y. Zakharov and B. L. Turcheninov, "Stiff" - A Program for Solving Rigid Systems of Ordinary Differential Equations," Institute of Applied Mechanics of the Academy of Sciences of the USSR, Moscow, 1971.
5. A. Q. Eschenroeder and J. A. Lordi, "Catalysis of Recombination in Non-equilibrium Nozzle Flows," *9th Symposium on Combustion*, 1962.
6. T. S. Sheshadri and V. K. Iain., "Propellant Gas Phase Chemical Kinetics," *Propellants Explosives, and Pyrotechnics*, Vol 14 p 193-198, 1989.
7. A. S. Bashkin et al., *Chemical Lasers*, Nauka, Moscow, 1982.
8. A. V. Pustogarov et al., "2 MW Hydrogen Plasmatron," 6th All-Union Conference on Low Temperature Plasma Generators. Summaries of Reports, "Ilim" Frunze, 1974.
9. A. S. Koroteev, *Arcjet Plasmatrons*, Mashinostroyeniye, Moscow, 1980.

III. REFRACTORY METALS FOR ARCJET ANODE APPLICATIONS

W-4Ta is one of the strongest materials in the world. CIS data shows that its creep strength surpasses W-Re-Hf-C polycrystalline material which was selected for study in several US efforts on high creep strength materials.

The advantages of single crystal refractory metal alloys can be observed from Tables 3-1 and 3-2, and Figures 3.1 through 3.4. Material compatibility, resistance to diffusion of carbon, and high creep resistance are the primary attractive properties of these alloys for thermionic emitter claddings.

Molybdenum single crystal alloys also exhibit much more impressive tensile properties at high temperatures than polycrystalline alloys. However, the molybdenum series does not exhibit the same high temperature tensile strength and creep resistance as the tungsten series.

Figure 2.2 illustrates the creep rate of several refractory metal materials at 1923 K. It is worth pointing out that some tungsten alloys, notably W-Re-HfC exhibit excellent mechanical properties, though W-4Ta is claimed to be slightly superior.

The results of accelerated creep testing are shown in Figure 2.3 for W-4Ta single crystal alloy and several other high creep strength materials developed in the US. The results show that W-4Ta offers superior characteristics to other materials.

Table 3-1 Some Properties of Molybdenum Single Crystal Alloys

Properties	Temperature			
	293 K	1723 K	1923 K	2273 K
Thermal Conductivity, W/mK	120-160	90-105		
Electrical Resistivity, $\mu\Omega$ cm	5-0-7.0		54-70	
Ultimate Tensile Strength, MPa	450-600	25-200		10-120
Steady-State Creep @ 10 MPa, %/hr		1.6×10^{-4}	1.6×10^{-3}	

Table 3-2 Some Properties of Tungsten Single Crystal Alloys

Properties	Temperature			
	293 K	1723 K	1923 K	2273 K
Thermal Conductivity, W/mK	100-130	90-110		
Electrical Resistivity, $\mu\Omega$ cm	5-0-8.5		54-70	
Ultimate Tensile Strength, MPa	1000-1500	50-200		15-150
Steady-State Creep @ 10 MPa, %/hr			$<10^{-3}$	

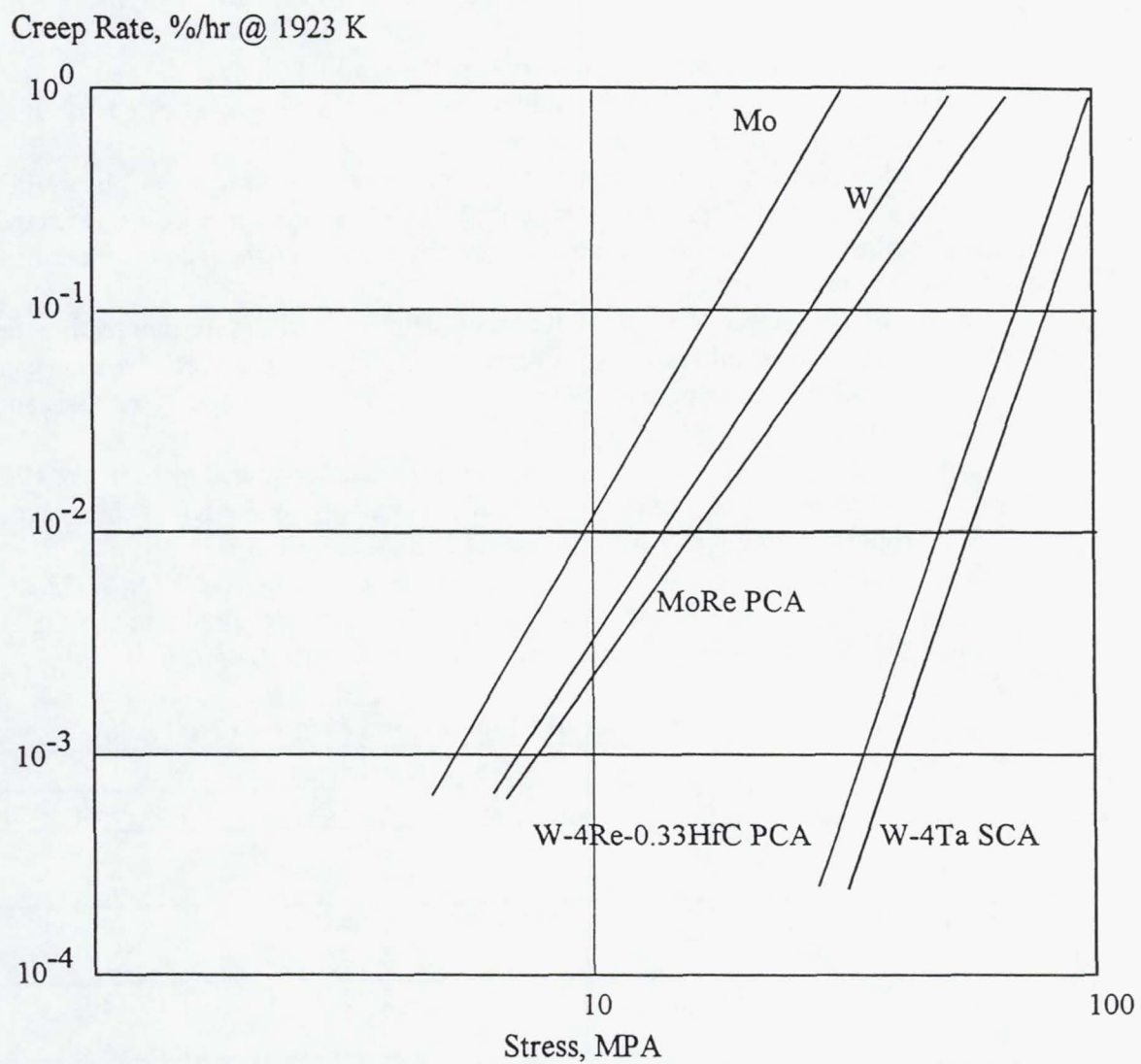


Figure 3.1 Creep Rate of Various Refractory Polycrystalline Alloys (PCA) and Single Crystal Alloys (SCA).

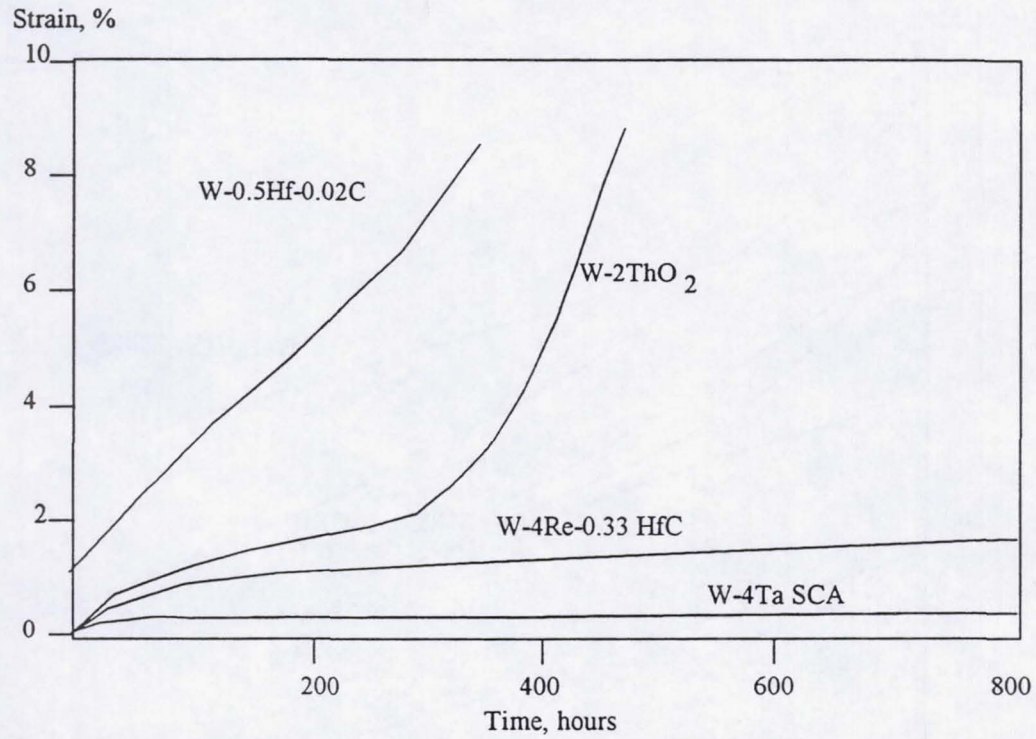


Figure 3.2. Strain vs Time at 1923 K for Various Materials

Figure 3.3 shows the 10^{-6} strain per second creep strength of several creep resistant materials.

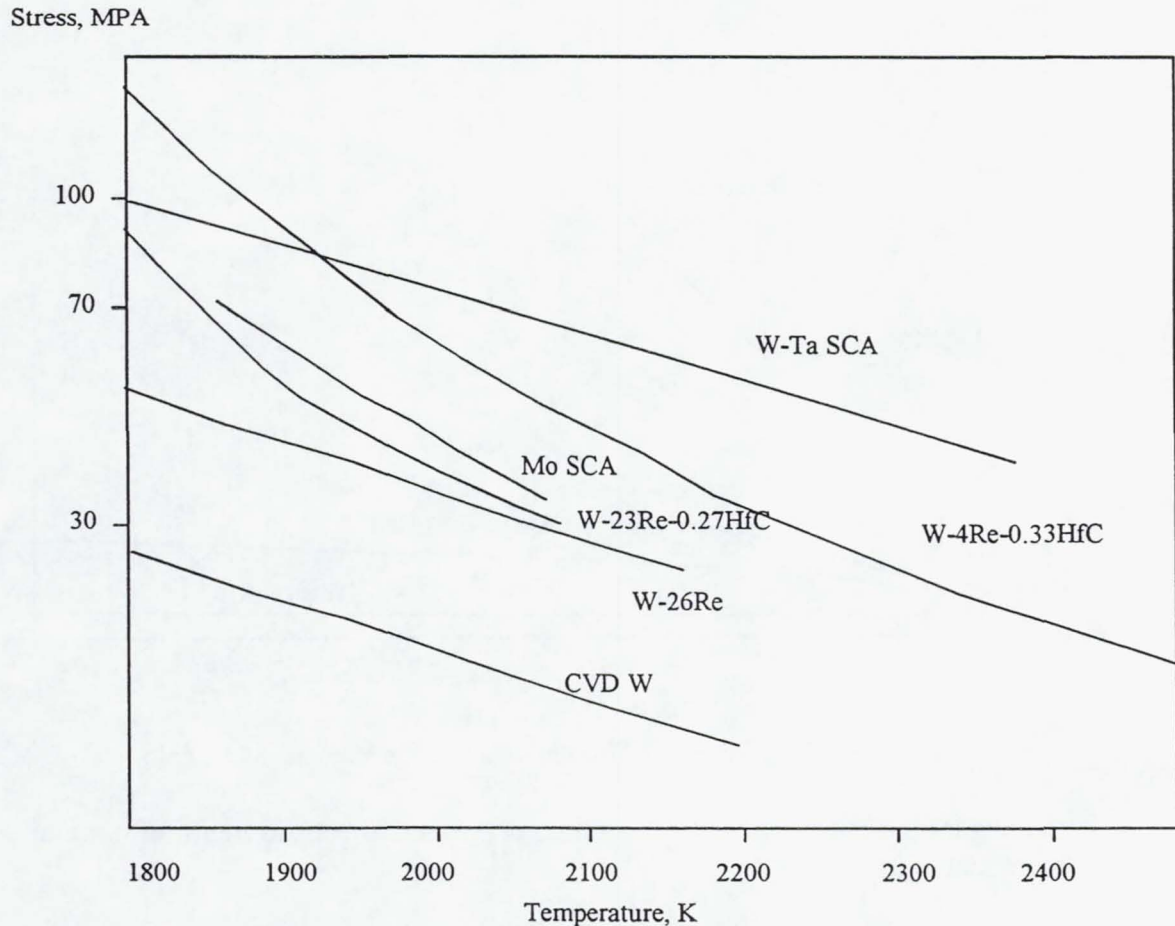


Fig. 3.3 10^{-6} /sec Creep Strength for Various Materials

Joining of single crystal refractory metal components is a complex process. Normal welding techniques can not be used without destroying the single crystal aspect of the metal. Zone refining can be used to make virtually undetectable joints between two pieces of the same material. However, it is extremely important to align the two pieces perfectly, otherwise defects result.

For this purpose, x-ray diffraction photographs must be used to make a precise alignment prior to zone refining.

We do not have access to protocols describing the procedures to be followed for making joints in the materials using this technique; only assurances from Luch that it can be done.

II.A FABRICATION ISSUES FOR ARCJET ELECTRODES

Because of the success of the technology for high temperature, high stress applications such as nuclear fuel element claddings, it makes sense to consider their use for other high temperature applications such as arcjet electrodes.

The following observations may apply:

a. In the case of the cathode, the tip of the cathode must be kept at a very high temperature in order to achieve high emission current. Under these conditions, the melting point of the cathode is one of the key features, not necessarily the tensile properties per se. Accordingly, the higher strength of these alloys may be irrelevant for the cathode.

b. For the anode, thermal stresses are a serious problem, and the availability of creep resistant materials is certainly important. Compared to pure tungsten, it is clear that these materials are far superior in terms of strength and creep resistance. However, the creep properties shown above indicate that the improvement over W-Re-HfC polycrystalline alloy is only an incremental one.

c. Although Russian institutes have begun to publish data concerning the properties of single crystal alloys, the material data base is still relatively skimpy. Efforts at NASA LeRC and elsewhere are confirming and improving upon the data given to us by Russian technologists, but more data must be accumulated to gain confidence in the properties of these materials. We are led to believe that large amounts of data have been accumulated by Russian specialists in support of the thermionic conversion programs, but this must be regarded as hearsay until technical documentation is available. Of particular weakness is data relevant to machining these materials; for example, fracture and shear resistance along crystalline planes would be very helpful. Defect density and variation of uniform crystal orientation would likewise be helpful in evaluating the quality of individual ingots.

d. We are told the two strongest candidates for high temperature, low creep applications are W-Ta and W-Nb. Of these two, W-Ta is said to be slightly superior. However, both have additives which form hydrides in reducing atmospheres. Therefore, hydrogen embrittlement and/or ablation must be considered as possible life-shortening factors for arcjet electrodes, particularly in view of the high temperatures and thermal cycling which are present.

e. We are also told that W-Ta is formed using a Czochralski technique; whereas W-Nb is manufactured using zone refining. The W-Nb is apparently difficult to fabricate in large specimens; i.e., as long as 10 cm. This statement again is something more than hearsay, but something less than substantiated scientific fact in the absence of good solid data.

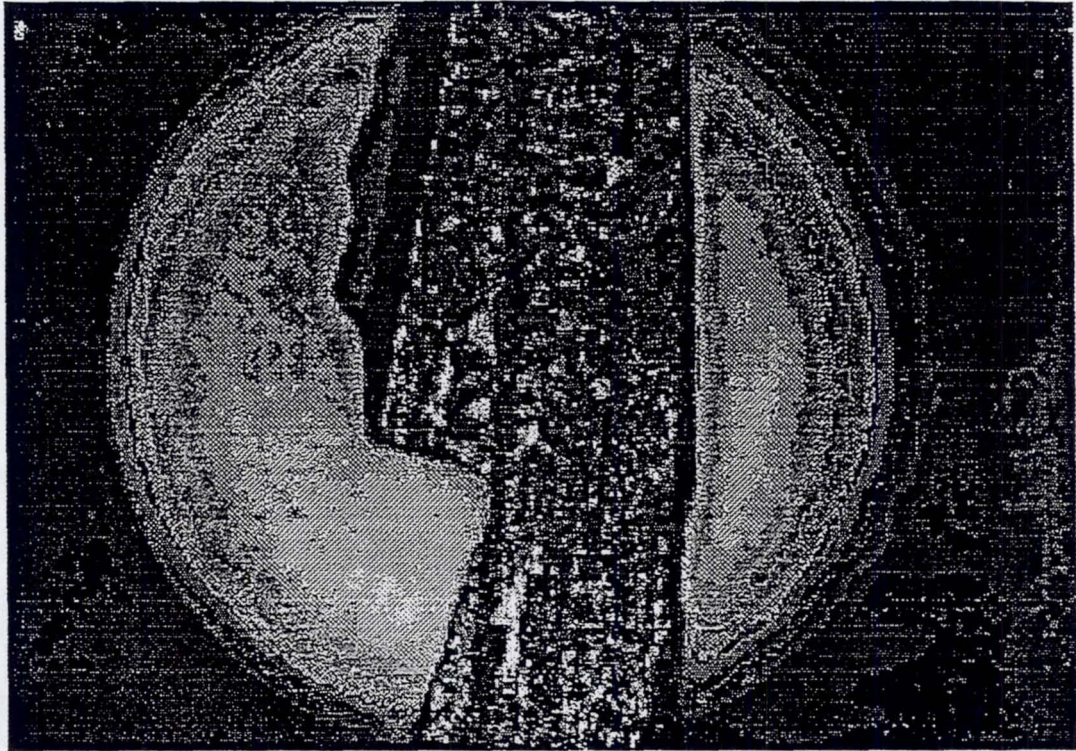


Figure 3.4. Fracture surface of single crystal shard, 50x magnification.

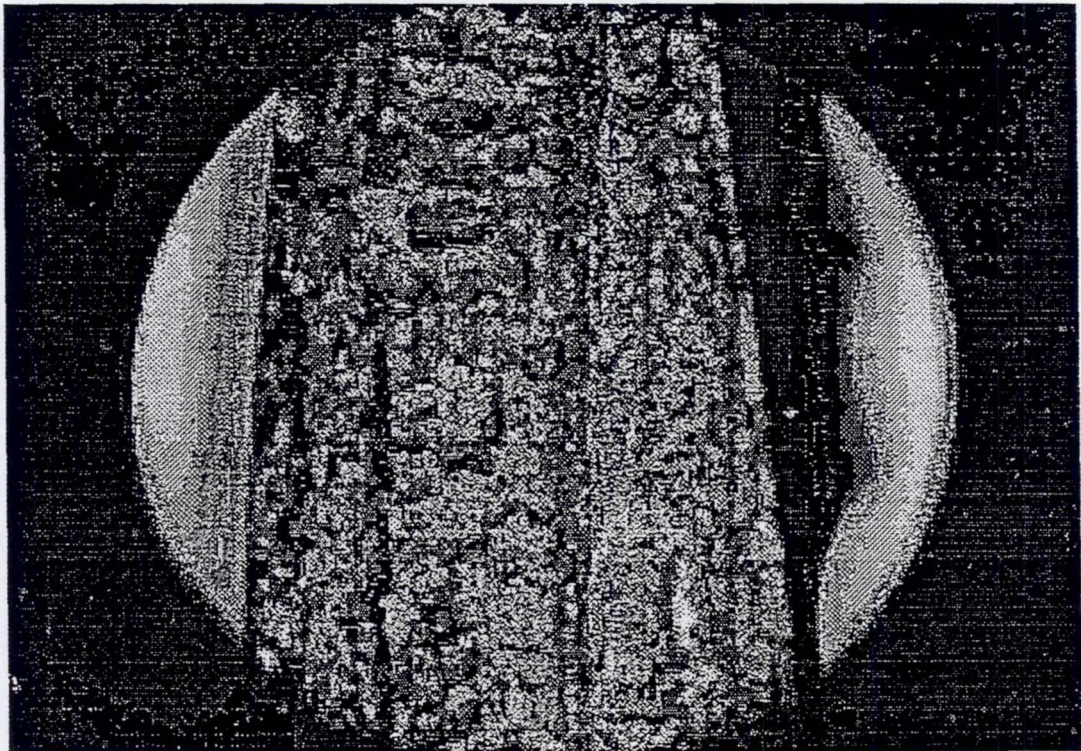


Figure 3.5. Fracture surface of single crystal shard, 100x magnification.

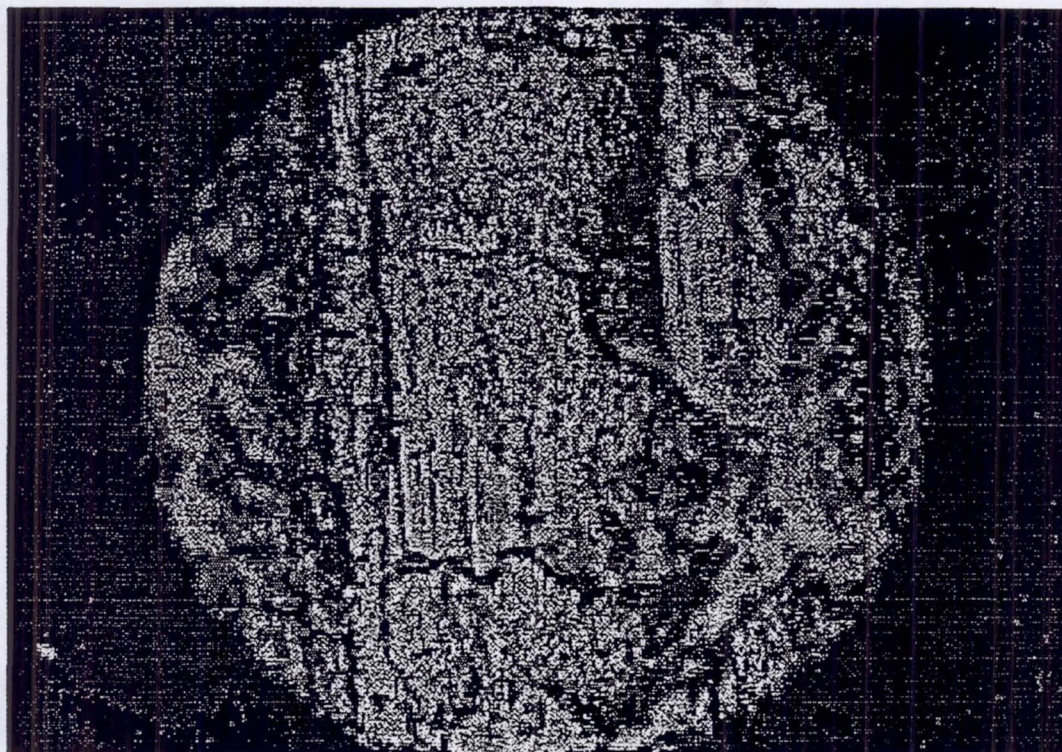


Figure 3.6. Fracture surface of single crystal shard, 400x magnification. Crystalline structure is suggested in this view.

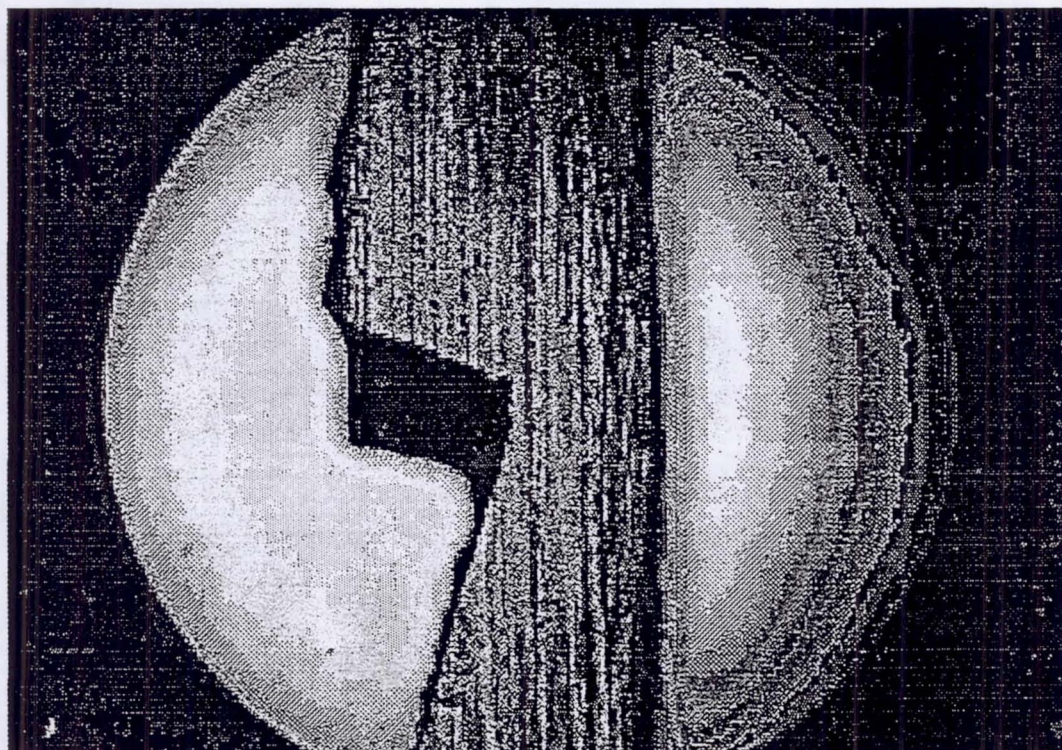


Figure 3.7. Crystal shard, cut by diamond saw, 50x. Cutting striations can be plainly seen.

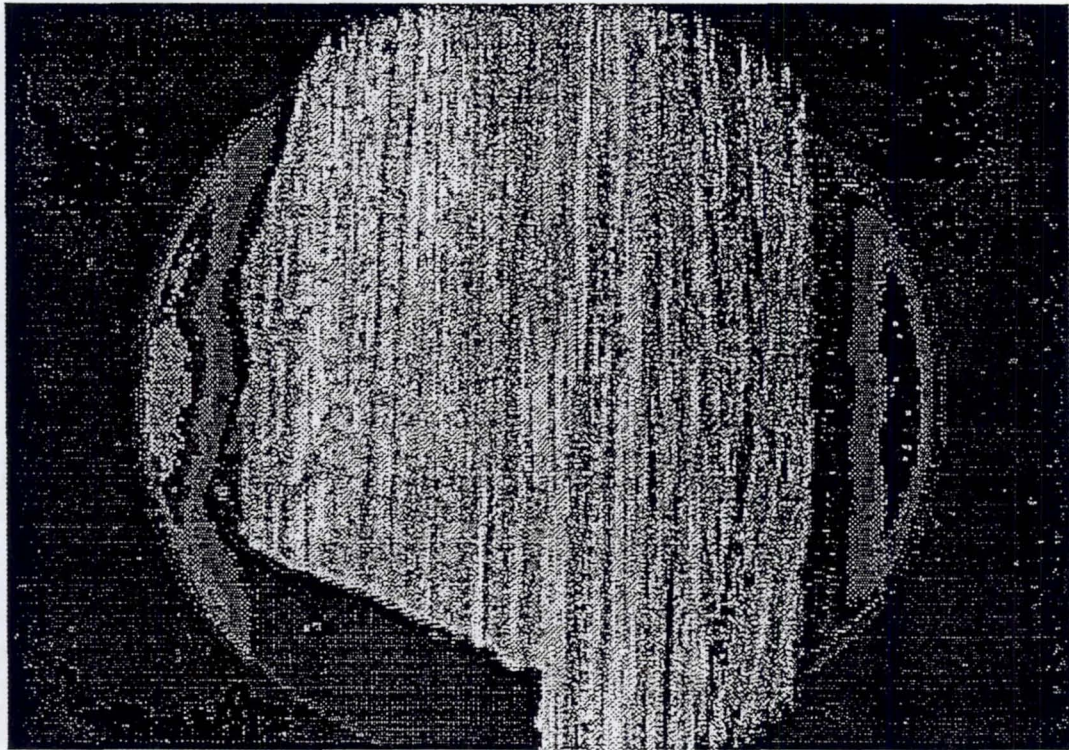


Figure 3.8. Crystal shard, cut by diamond saw, 100x. Cutting striations can be plainly seen.

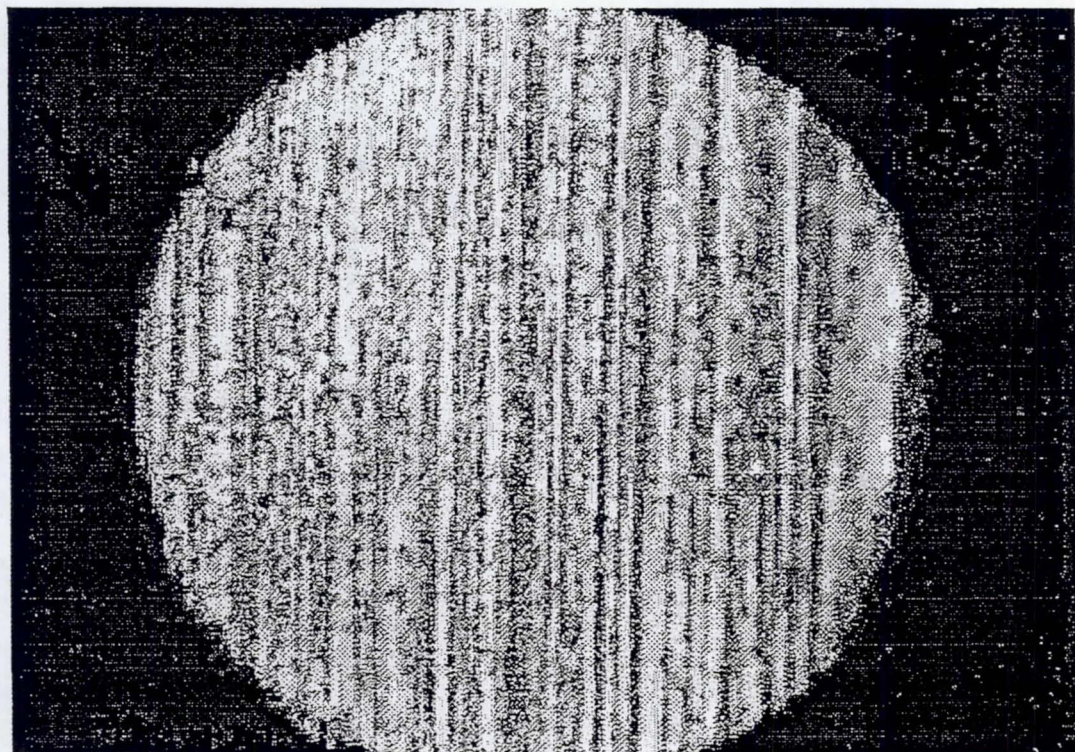


Figure 3.9. Crystal shard, cut by diamond saw, 400x. Cutting striations can be plainly seen, but some crystalline structure is barely perceptible in the original photograph.

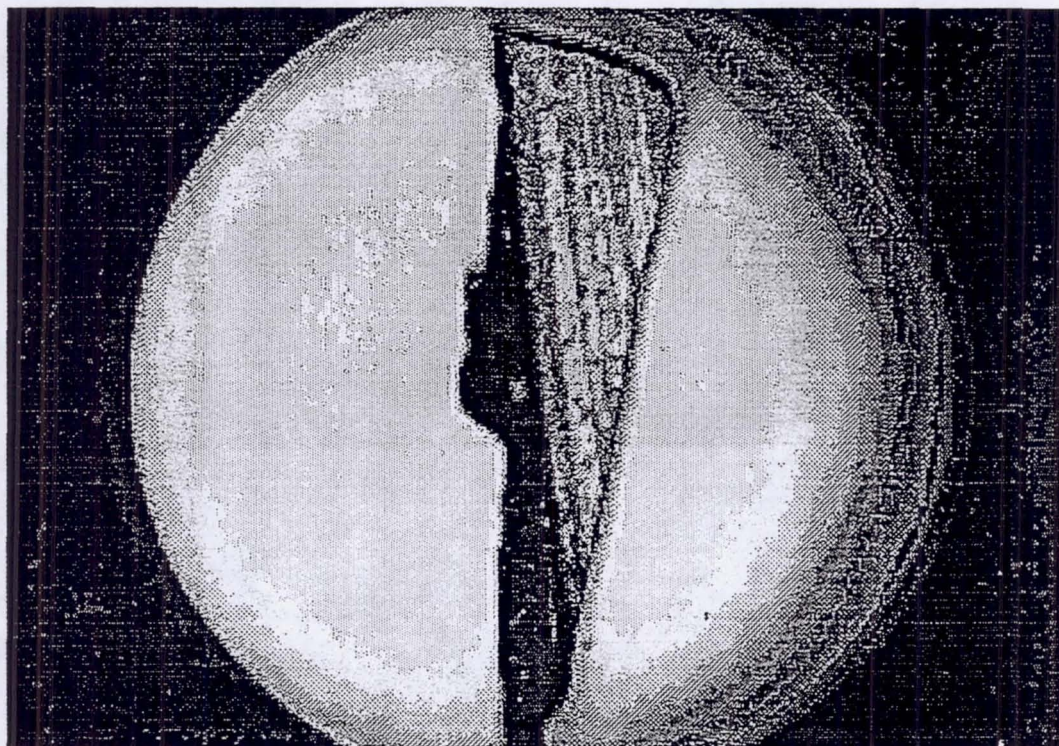


Figure 3.10. Crystal shard, showing machining marks from NPO Luch, 50x.

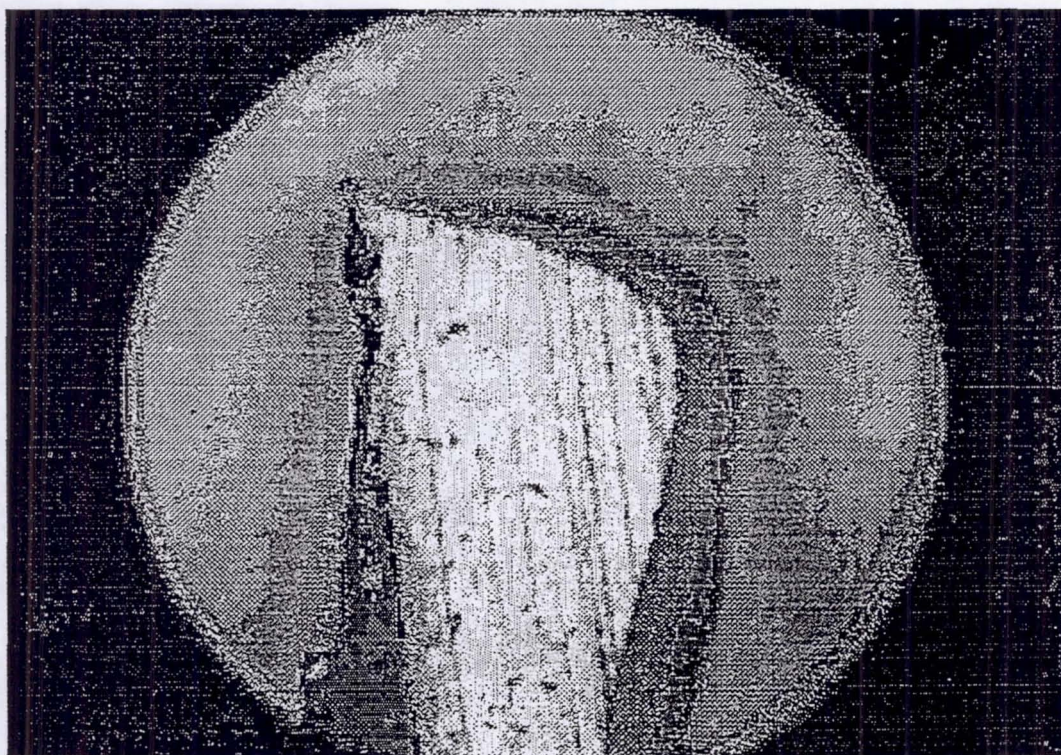


Figure 3.11. Crystal shard, showing machining marks from NPO Luch, 100x. Some pitting is also visible.

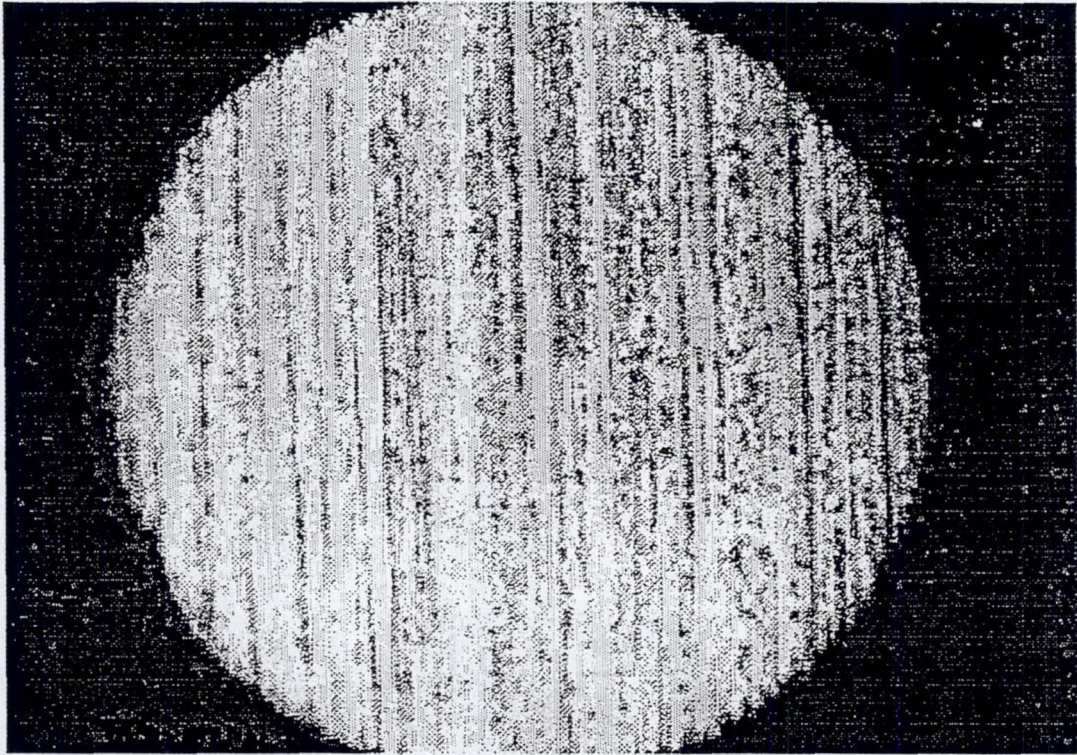


Figure 3.12. Crystal shard, showing machining marks from NPO Luch, 400x. Pitting is also clearly visible.

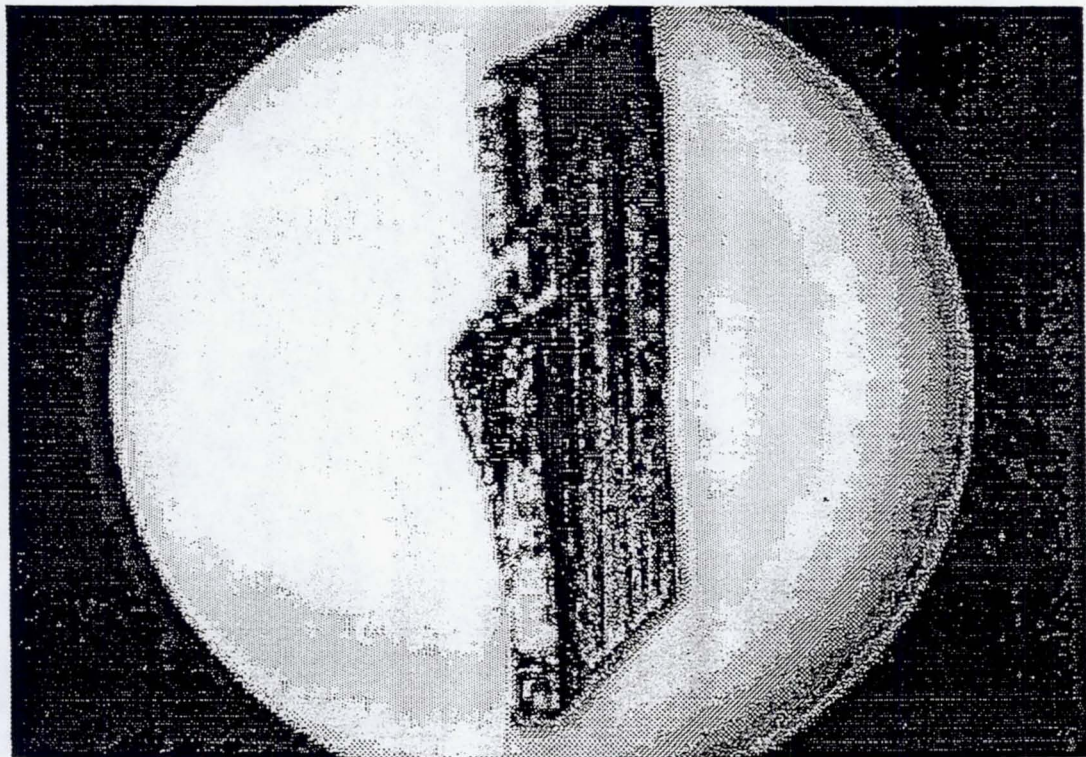


Figure 3.13. Edge-on view; smooth surface, 50x.

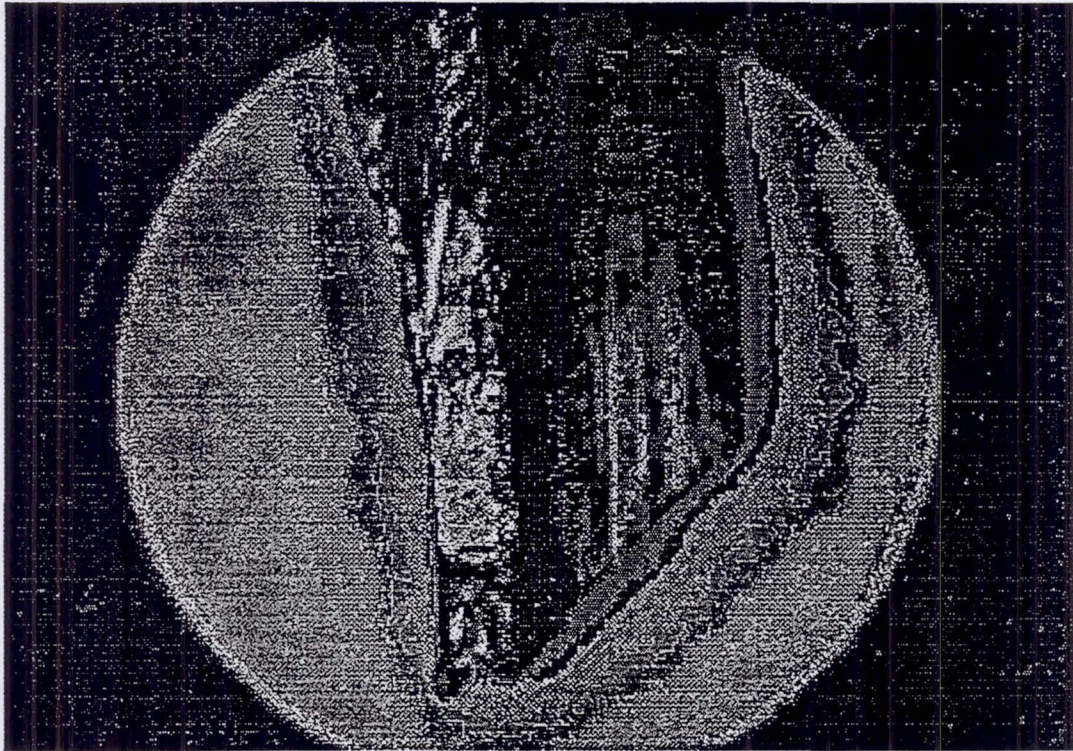


Figure 3.14. Edge-on view, smooth surface. Crystalline structure is suggested 100x.



Figure 3.15. Edge-on view, 400x. Some suggestion of frozen metallic structure is observed in the original photograph.



Figure 3.16. SEM photomicrograph of fracture zone, clearly displaying crystalline layers.

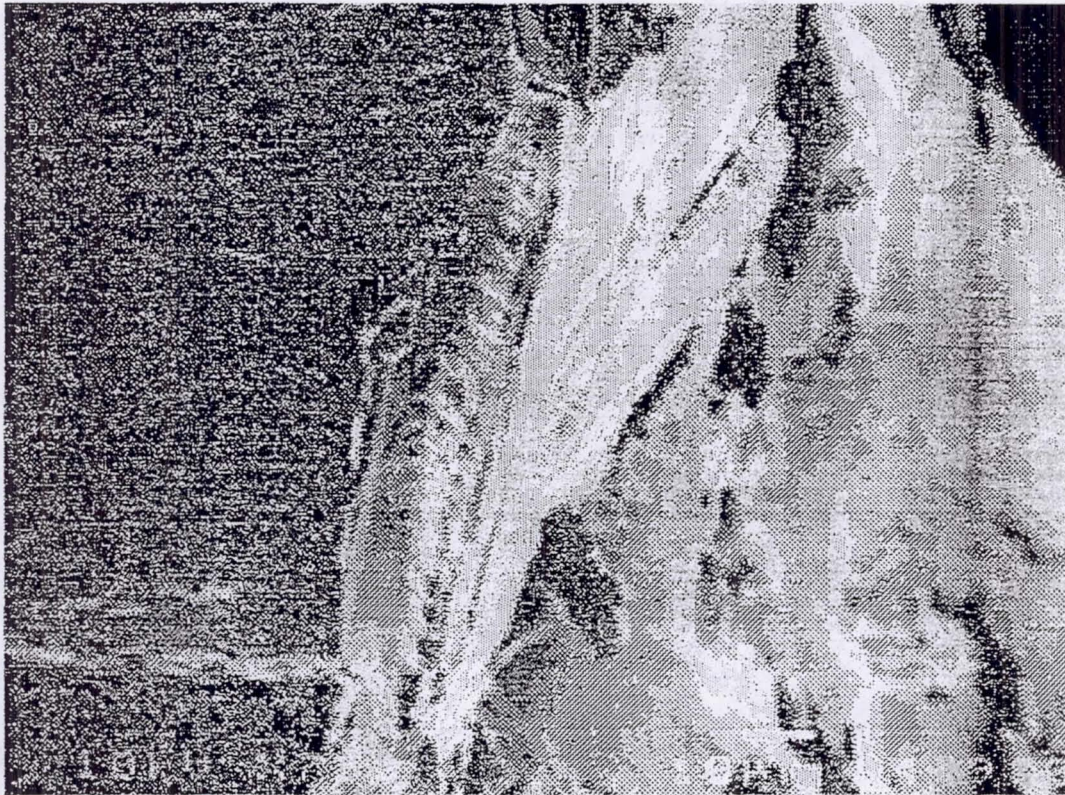


Figure 3.17. SEM photomicrograph, with a slightly different view than used on Figure 13.

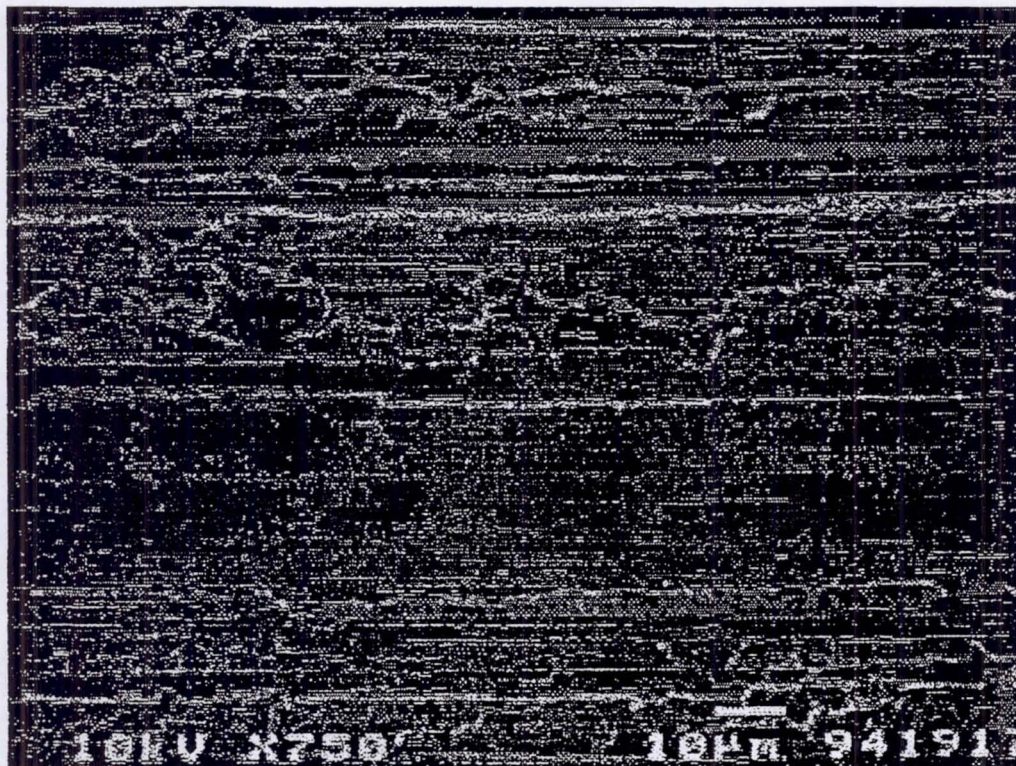


Figure 3.18. SEM photomicrograph of Luch-machined area. Crystalline layer structure can also be observed.

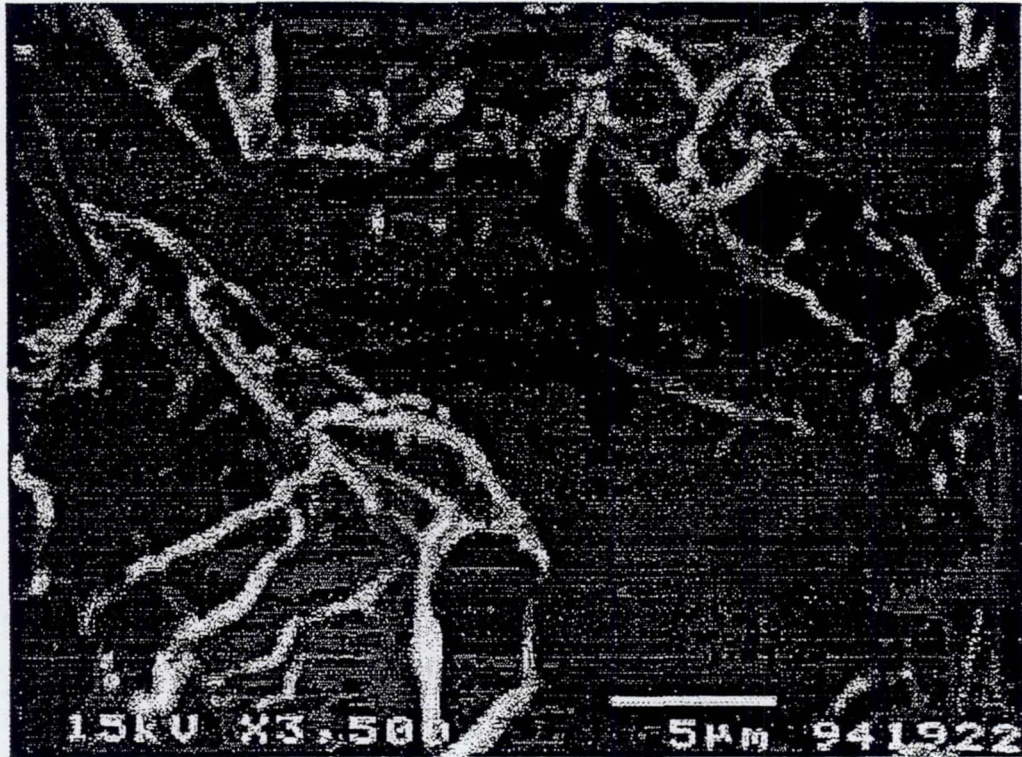


Figure 3.19. SEM photomicrograph of fracture area. Crystalline planes are clearly observable.



Figure 3.20. SEM Photomicrograph of fracture surface. Crystalline planes are clearly visible.

IV. CARBON COMPOSITES FOR ARCJET ELECTRODES

A new generation of carbon composites makes it possible to consider composite anodes for arcjet engines. Because of the excellent high temperature tensile properties of carbon-carbon which can now be combined with high electrical conductivity, it is possible that these materials can be attractive for arcjet anodes providing that refractory carbide coatings such as tantalum carbide, hafnium carbide or niobium carbide, can be shown to have adequate resistance to attack from reducing atmospheres such as hydrazine or hydrogen.

Moreover, for NIITP designs which attempt to obtain higher cathode lifetime via a rotating arc, carbon-carbon composites are expected to support higher current densities at with smaller thermal transients than the copper anodes now in use. In addition to the much higher temperature capability of carbon-carbon, it also has a much higher thermal diffusivity, and thus will minimize the effects of thermal cycling. It must be added, however, that US experts currently do not accept NIITP claims for enhanced cathode lifetime and performance through this design.

The key to an arcjet anode with high thermal diffusivity and low electrical resistivity is the use of vapor grown carbon fiber (VGCF).

Of greatest current interest is the ultra high thermal conductivity of VGCF, which exceeds that of any other carbon fiber. Thus VGCF reinforced carbon composites (VGCF/C) are attractive for use in numerous high heat flux applications.

VGCF is produced by the decomposition of hydrogen/methane gas mixtures in a two step process. First is growth, which is accomplished via a catalyzed deposition reaction. A hydrogen-methane mixture is decomposed at around 800 C, with the aid of a iron or nickel-based catalyst. The catalyst, in the form of a small ball about 10 nm in diameter, is believed to function as a nucleation point for carbon fiber growth. As carbon atoms impinge upon the metal ball, it is presumed that they are very mobile. However, as the carbon atoms begin to impinge upon each other, they bond securely in a graphitic bond. Rather than forming a plane, however, the graphitic sheet wraps around itself to form a cylindrical sheath, as depicted very schematically in Figure 4.1 (for the sake of simplicity, only a few atoms are shown. Actually, the dimensions of the catalyst must be on the order of 10^2 to 10^4 carbon atoms in order to promote the formation of a cylindrical sheath).

Thus, the metal catalyst acts as a sieve for pyrolytic carbon atoms, with the result being that carbon fibers are nucleated and grown from the catalyst particle. These fibers can grow up to several cm long.

In the second stage, graphite fibers are fattened by elevating the temperature by some 300 °C and increasing the concentration of hydrocarbon gas. The result is that additional layers of pyrolytic carbon are deposited. Thus, unlike virtually all other graphite fibers, which have a radial geometry, VGCF fibers grow in an "onion skin" geometry as depicted in Figure 4.2.

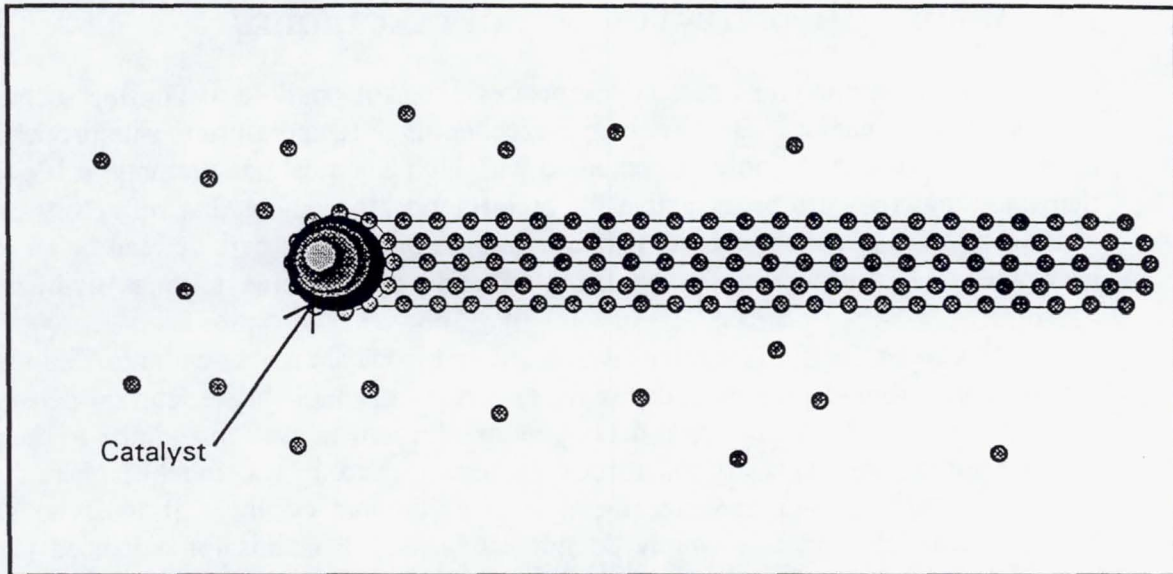


Figure 4.1. Nucleation of Carbon Fiber by Metal Catalyst

There are several different versions of VGCF. One version is grown with the catalyst particles imbedded in a solid substrate. The fibers thus grow attached to the substrate. Depending on the orientation of the substrate surface versus gravity and the flow direction of the precursor gasses, the fibers can be grown in a mat, or in a short staple tow. This process is a batch process, although work is progressing on developing a continuous fiber with similar characteristics.

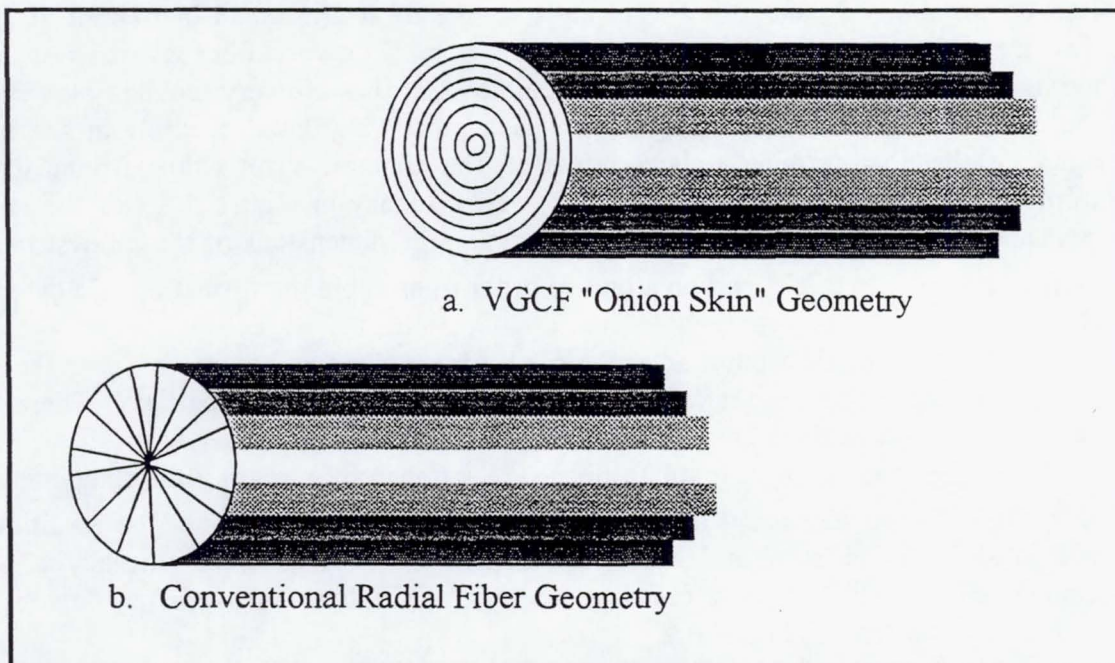


Figure 4.2. Illustration of Fiber Geometry

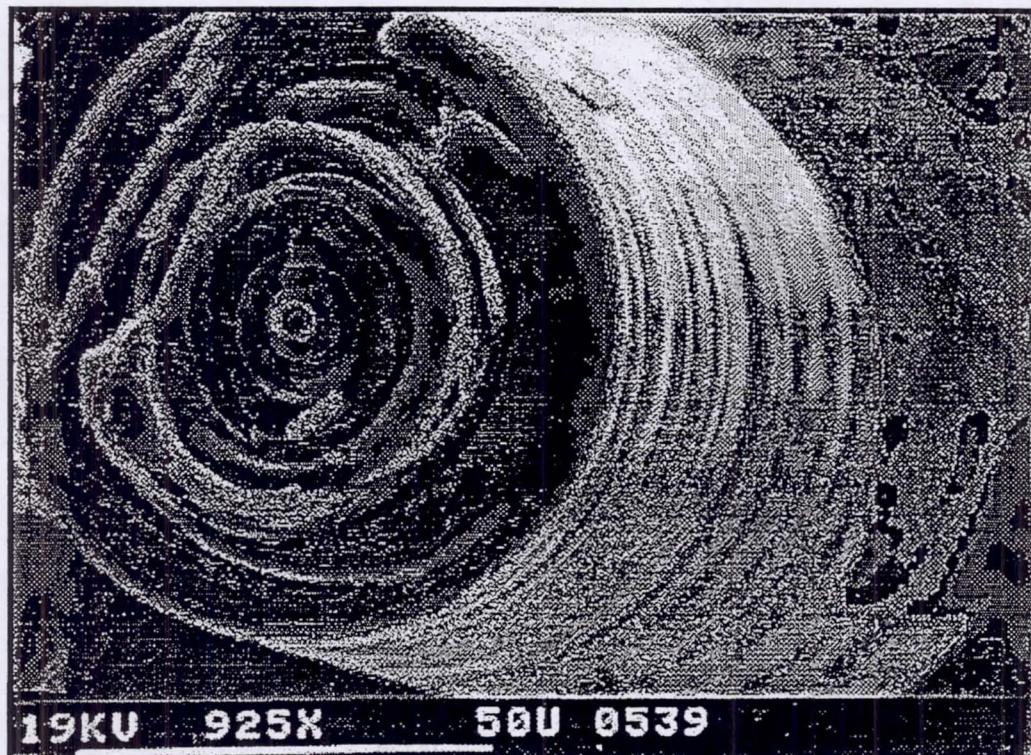


Figure 4.3. Electron Photomicrograph of 100 μ Diameter Fiber Cross-Section

The purity of the carbon source and the mechanics of fiber growth result in a highly graphitizable fiber with a unique lamellar morphology and physical properties approaching those of single-crystal graphite. Single fiber properties of VGCF are summarized in Table 4-1.

The property which has been shown to have the greatest short-term potential for exploitation as an engineering material is the thermal conductivity. As shown in Table I, single filaments of VGCF heat treated at 3000 C exhibit an extremely high thermal conductivity approaching 3000 W/m-K at 150 K, and a room-temperature thermal conductivity of 1950 W/m-K.¹ VGCF has a unique microstructure, as shown in Fig. 1, in which the graphitic basal planes have a high degree of preferred orientation and are nearly parallel to the fiber axis.^{2 3} As a result, VGCF is more graphitizable than ex-PAN fibers and pitch fibers, thus accounting for the excellent physical properties shown in Table 4-1. Figure 4.4 compares the thermal conductivity, as well as electrical resistivity, of VGCF to other carbon fibers and metals.

Table 4-1. Physical and Mechanical Properties of Single-Fiber VGCF.

Property	As-Grown	After Annealing @ 2800 C
Length, cm	10^{-3} - 30	10^{-3} - 30
Diameter, cm	10^{-3} - 30	10^{-3} - 30
Density (g/cm^3)	1.8	2.0
Tensile Modulus (GPa/Mpsi)		
lower bound	230/33	360/52
upper bound	400/58	600/87
Tensile Strength (GPa/Mpsi)		
lower bound	2.2/0.31	3.0/0.43
upper bound	2.7/0.39	7.0/1.0
Ultimate Strain (%)	1.5	0.5
Electrical Resistivity ($\mu\Omega\text{cm}$)	1000	60

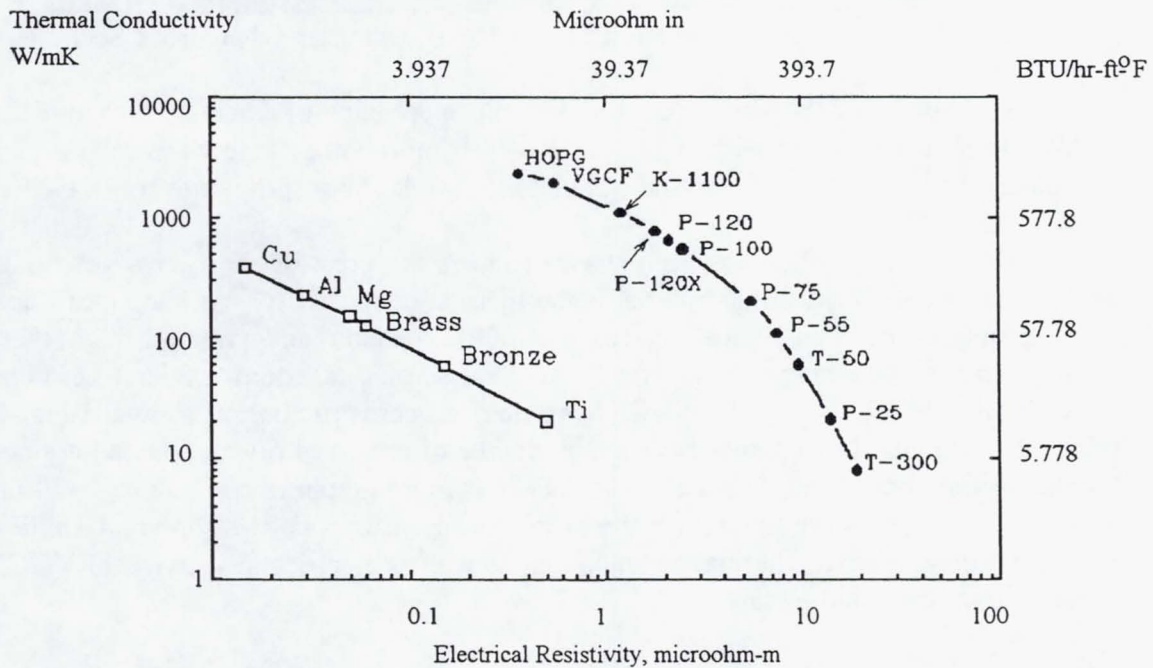


Figure 4.4. Thermal Conductivity and Electrical Resistivity for Metals and Carbon Fiber.

VGCF/Carbon Composites

Since their earliest development, composite materials have mostly been used for various structural applications. Recently, applications for composite materials in thermal management have emerged. ⁴ Thermally active composite materials meeting demanding

criteria for density, conductivity, and cost have been demonstrated. VGCF/C composites, having a density lower than aluminum and a thermal conductivity three to four times that of aluminum, is seen to hold significant potential for high performance thermal management components. Steps remaining in the exploitation of VGCF reinforced composites include refinement of methods for composite fabrication and the evaluation and optimization of thermal and mechanical properties of the composites. Towards these goals, effects of fiber loading, composite density, and densification method on VGCF/C composite properties have been studied and some results are presented below.

The use of reinforcing fibers greatly enhances the properties of a monolithic material. The benefit of using higher fiber volume fractions (FV) is realized only to the limit where adverse effects from fiber packing occurs. The limit is determined by factors including packing efficiency and fiber damage. The latter is particular true when highly graphitic carbon fiber, normally brittle, is used. For the initial development of VGCF/C composites, we have investigated the effect of fiber loading and fiber brittleness on properties of the resulting composites.^{5 6}

These preforms are then densified by the chemical vapor infiltration technique at about 1050 C in a gaseous mixture of about 80% CH₄ and 20% H₂. The densification time can be varied in order to obtain different final densities.

The best thermal conductivity measurement to date is 910 W/mK at room temperature; however, even higher values should be possible with improved graphitization of the carbon matrix surrounding the fibers, given that the starting thermal conductivity of the fiber alone is ~1950 W/mK.

Liner Technology

The key to successfully incorporating a carbon-carbon anode or nozzle in an arcjet will be to line it with a protective material. Carbon-carbon itself is chemically attacked by hot hydrogen, and thus there is no question that it must be protected with an inert liner. The liner must be able to withstand erosion over the lifetime of the thruster, and must be able to conduct heat and electric current.

Two possibilities exist. The first is to use rhenium metal, which is one of the few refractory metals to not form a carbide at high temperature. Moreover, rhenium is impervious to attack by hydrogen. A small amount of carbon will diffuse through rhenium, which may tend to degrade its structural properties over time. This needs to be characterized with life testing to ensure that rhenium will be durable enough for specific mission requirements.

Rhenium metal liners for rocket nozzles have been successfully demonstrated in the past by TRW, but not for arcjet applications. Long duration integrity of the liner is the predominant concern here. The largest unknown for rhenium is the effect of long term thermal cycling. Adherence of the liner to a carbon-carbon substrate should be verified under prototypic conditions.

In order to increase the adherence of rhenium to the carbon-carbon liner, an ion beam injection technique could be used to form an effective bond between carbon-carbon and rhenium surfaces despite the fact that there is no chemical affinity between carbon and rhenium. Once a layer of ~0.5 microns of rhenium is deposited on the surface of the

anode, it would then be possible to add additional thickness via chemical vapor deposition or a similar technique.

Ion beam implantation techniques have come into increasingly common use in the past decade. Ion implantation is the process of introducing atoms of alloying elements into the surface layers of a solid material by accelerating the atoms to high energies (50 to 200 kilovolts) and allowing them to strike the surface of the material. The energetic ions penetrate into the surface of the material to depths ranging from 0.01 to 1 micron depending on the energy of the ion, thereby creating a thin, mixed surface layer.

When the ions interact with the target atoms, two forms of energy loss occur. These are elastic scattering, and inelastic scattering. In the latter, interaction of the ion with the electrons of the target material atom causes the target atom to be displaced. If the displaced atom receives sufficient energy, it may cause additional displacements in a subsequent collision cascade. These additional displacements continue until no atom in the cascade has sufficient energy to cause displacements, generally in the range of 25 eV. In the region which encompasses heavy ion cascade, (1,000 to 10,000 atoms) between 10% and 100% of the atoms in the target may be displaced. The considerable rearrangement of atoms in the target is known as ballistic cascade mixing.

Typically, chemical bonds have a strength on the order of electron volts. Because of the very high energy of the ion beam, extremely rigorous bonding occurs *at the atomic level*. The ions are fired into the host lattice with sufficient energy that there is no other possibility but for them to bond into the lattice, regardless of their chemical compatibility. Thus material interfaces created using this method are likely to not de-laminate.

Indeed, this method has been used to make metallurgically "impossible" bonds such as copper-to-glass, copper-to-rubber or gold-to-molybdenum. Material deposited with ion beams does not come off with the so-called Scotch-tape test, epoxy test or any other method except the grinding wheel. Thus, it is very important to understand that the use of high energy ion accelerators is fundamentally different than CVD, plasma spraying or other conventional techniques. This is why we are confident that we can create adherent bonds where conventional methods fail.

Since the atoms are implanted ballistically and not through thermal action, there is no need for the application of high temperatures.

Furthermore, the coatings applied in this manner are in compression at ambient temperature, and relax as the substrate expands. Thus, the coatings are not only very thin and adherent, but internal stress is relieved as the substrate is heated. Thus the ability to withstand substantially mismatched thermal expansion coefficients, especially for the case in which the substrate thermal expansion coefficient is higher than the coating, is excellent.

Graded interfaces, with maximum implanted atom concentrations at the surface of the implanted material can be produced with a variation of direct ion implantation termed ion beam mixing. In this process, a thin layer of one atomic species is deposited on the surface of the material to be implanted. A beam of chemically inert atoms (typically, argon or xenon is used) is then used to mix the overlayer into the substrate. Due to the highly concentrated source overlayer, ion beam mixing is not limited by sputtering effects, and the concentration of beam-mixed atoms on the substrate surface can approach 100 atomic weight percent. The concentration gradients and distribution profiles can be tailored by proper choice of beam mixing species, doses and energies. The absence of a

discontinuous interface between the mixed surface layer and the bulk material leads to excellent adhesion of the layer and less sensitivity to mechanical failure at elevated temperatures and during thermal cycling.

Ion beam enhanced deposition uses high energy atoms to adherently bond the atoms of a coating to the substrate. For example, in the case of silicon nitride or boron nitride, silicon (or boron) would be deposited via ion beam induced sputtering. Simultaneously, nitrogen ions will be fired onto the substrate, combining with the boron and mixing the atoms at the atomic level. This is shown conceptually in Figure 4.5. For purposes of clarity, the numbers of atoms are greatly reduced, and a simple homogeneous array of atoms is depicted.

Ion beam mixing can be used to produce layers of metallic or other materials which will grade continuously into the surface of the substrate. This is accomplished by first depositing a thin layer of material (typically less than a micron) on the surface of the substrate. Then an inert gas ion beam is used to bombard the surface, knocking atoms from the coating material into the substrate at high energies, thus causing a ballistically-induced physical bond. This technique is often used when relatively thick coatings are required, or when a graded interface is desired. That is, the concentration profile will smoothly change from 100% substrate to 100% coating material over a 0.5 micron depth. Since ion-beam mixed surface layer is a graded interface, interfacial stresses will be minimized during temperature cycling, and the mechanical stability of the surface layers will be increased, thereby eliminating cracking and spalling. The graded layer will also be bonded more effectively to the substrate surface since it is physically mixed into the composite surface. The result is an exceptionally strong bonded surface.

This is expected to result in an excellent capability to withstand thermal cycling, thermal shock and to minimize the effects of thermal expansion coefficient mismatches within wide limits.

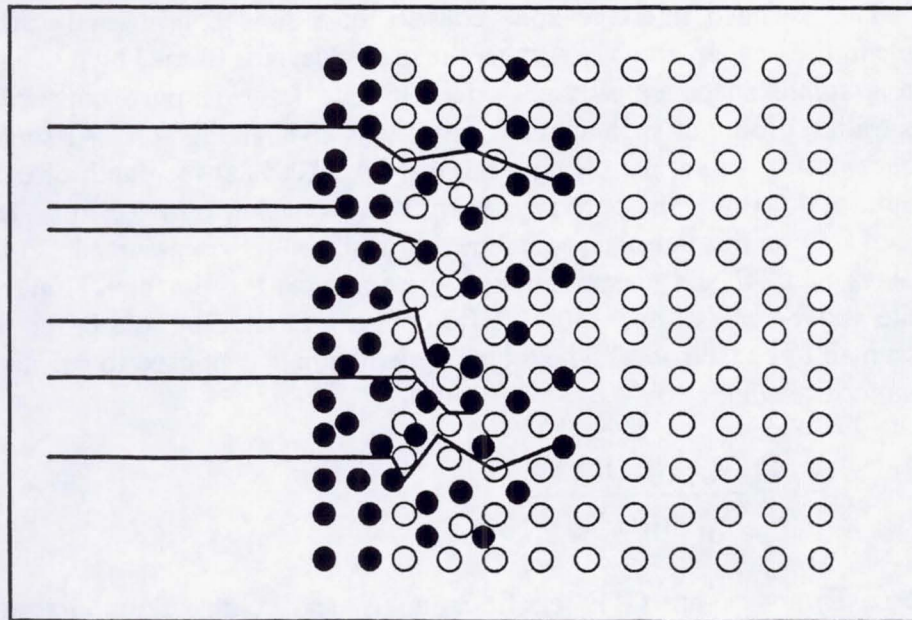


Figure 4.5. Conceptual Illustration of Ion Beam Enhanced Deposition, by Which Dissimilar Materials can be Adherently Bonded at the Atomic Level.

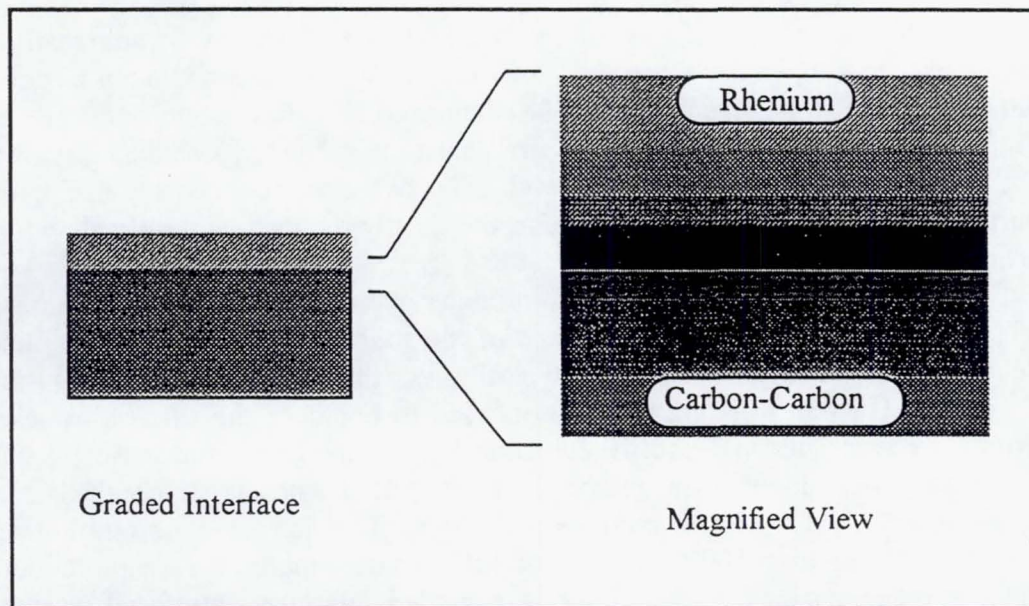


Figure 4.6. Conceptual Drawing of Graded Interface Produced at Microscopic Level. The Graded Interface can be ~0.5 Microns Thick.

Work with other dissimilar materials has shown that exception bonding can be produced using these techniques. An example using a rule of mixture (ROM) analysis, neglecting anisotropy, is given below for the example of copper on graphite, which we tested previously. These studies were carried out by J. M. Ting and M. L. Lake of Applied Sciences, Inc.⁷

The assumed interface zone consists of a graded layer and surface layer; for example in the copper-graphite system, the graded layer is formed by mixing copper atoms into a graphite specimen surface. The surface layer is pure copper. The copper concentration profile of such an interface zone is given in Fig. 4.7. As seen in this figure, the concentration of copper changes linearly from 100% at the depth of 0.5 μm to 0% at the depth of 4.0 μm . The pure copper layer has a thickness of 0.5 μm . To calculate the profile of CTE in this interface zone, the following values are assumed. In the calculation, the values of CTE and elastic modulus were assume to be 4 ppm/K and 27.5 GPa for graphite and 17 ppm/K and 110 GPa for copper. In addition, the properties of graphite are assumed to be isotropic. The following equation is then used to calculate CTE values in the interface zone:

$$\alpha = \frac{\alpha_{gr} E_{gr} V_{gr} + \alpha_{Cu} E_{Cu} V_{Cu}}{E_{gr} V_{gr} + E_{Cu} V_{Cu}}$$

where α , E , and V are CTE, elastic modulus, and volume fraction respectively. The subscripts gr and Cu designate graphite and copper respectively. Accordingly, the results are plotted in Fig. 4.8. As shown in this figure, by mixing copper atoms into graphite to

create a graded layer and depositing an additional layer of copper, the value of CTE changes gradually from that of graphite to that of copper. In addition to this advantage, through IBED processing the joining of two dissimilar materials, graphite to copper, becomes identical to the joining of the same material (copper to copper).

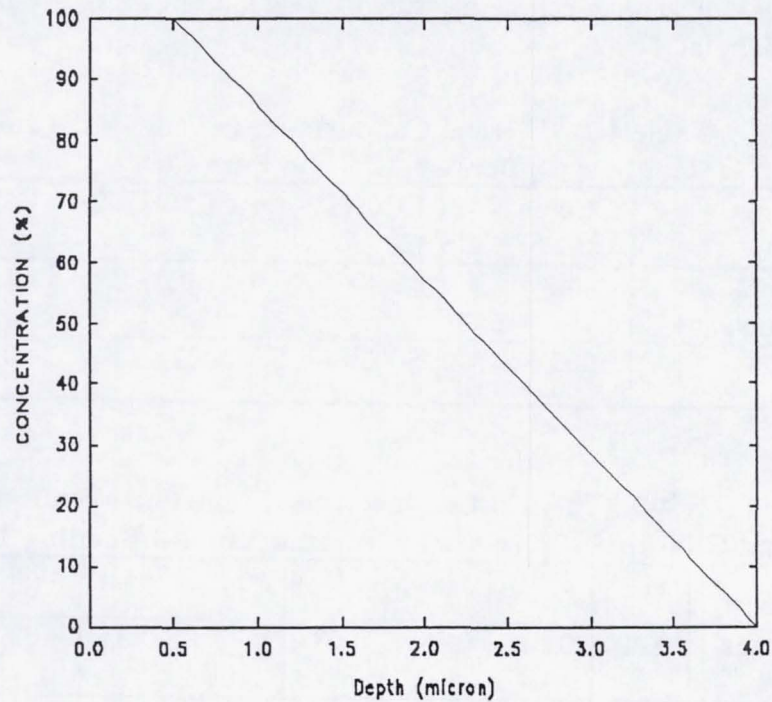


Figure 4.7. Graded Interface, from Rutherford Backscattering Data.

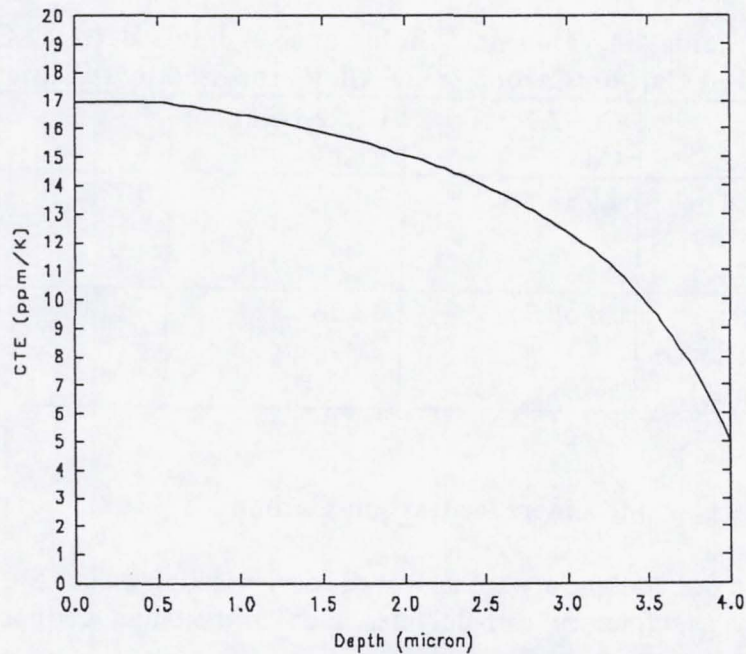


Figure 4.8. Calculated CTE Profile, Based on RBS data

Evidence that the technology results in exceptional bonding between materials which are normally not thought to be chemically compatible is contained in the studies performed by Ting and Lake in the beryllium-Glidcop™ system.⁷

Bonds produced using our ion beam method have a very high thermal conductance--higher than can be measured. This indicates a nearly perfect joint from a thermal standpoint.

Table 4-2. Thermal Conductance (W/cm²-K) of Joints Between C/C and Pure Cu.

ID	CC04HT-Cu	CC09HT-Cu	CC10HT-Cu	CC12HT-Cu
Thermal Conductance	14.42	10.40	11.93	14.96
Filler	5003	5003	5003	5012

Table 4-3. Thermal Conductance of Joints between K-Karb™ and Glidcop™ Processed by Infrared Assisted Bonding Technique.

ID	#1	#2	#3	#4	#5	#6	#7	#8	#9
Conductance (W/cm ²)	0.42	0.21	0.43	0.67	0.77	0.43	0.79	0.21	0.48
Process Temp (°C)	1050	1020	1050	1040	1020	1020	1020	1010	1000

Table 4-4. Thermal Conductance of Joints Between Glidcop™ and Carbon/Carbon or Be Alloy Processed by Diffusion Bonding.

ID	CC92.14HT-Cu1	CC92.14HT-Cu3	Be-Cu1	Be-Cu2
Thermal Diffusivity (Wcm ² /K)	1.782	2.033	0.772	0.774
Thermal Conductance (W/cm ² K)	24.55	38.36	~inf	~inf

Refractory Carbide Liners for Carbon-Carbon

A more straightforward approach for fabricating a liner for carbon-carbon may be to employ a refractory carbide liner such as tantalum carbide, niobium carbide or zirconium carbide.

Such materials were developed in the 1960s for coating nuclear rocket fuel elements, which were exposed to high pressure supersonic hydrogen at temperatures of 2700 K. Thus an extensive body of data exists on the properties of these materials. General properties of refractory carbides are high melting point, excellent wear and corrosion resistance, low vapor pressure and sublimation rate, and excellent hardness. Electrical resistivity is typically a few times higher than that of pure refractory metal, which is acceptable for high current electrode applications.

For long exposures and thermal cycling in a hydrazine environment, probably the largest issue is whether the coatings can remain sufficiently crack free to prevent corrosive attack of the underlying carbon-carbon. Moreover, the presence of nitrogen in the hydrazine will probably lead to the formation of a carbonitride phase on the surface, which may have somewhat different properties than the pure carbide.

Table 4-5. Summary of Properties of Refractory Carbides.¹⁰

Property	TiC	ZrC	HfC	NbC	TaC
Mol Wt	59.91	103.23	190.61	104.92	192.89
Density, g/cm ³	4.93	6.9	12.6	7.56	14.3
Heat of Formation, kJ/mol	0.183	0.184	0.338	0.14	0.15
Entropy kJ/molK	24.2	35.6		37.6	41.9
Specific Heat, kJ/molK	50.6	61.0		37.2	36.5
T _{melt} , K	3413	3803	4163	4033	4153
Thermal Expansion Coeff, 10 ⁻⁶ K ⁻¹	7.74	6.73	6.06	6.50	8.29
Thermal Cond @ 293 k, W/mK	29.0	54.7	16.7	38.0	59.2
Electrical Resistivity @ 293 k, μΩm	0.52	0.50	0.45	0.51	0.42
Thermal Coeff of Resistivity, K ⁻¹	1.16	0.95	1.42	0.86	1.07
Microhardness, GN/m ²	31.4	28.7	28.4	19.2	15.7
Modulus of Elasticity, 10 ³ kg/mm ²	46.0	36.5		34.5	29.1

Figures 4.9 to 4.28 are taken from reference 9. They summarize the temperature-dependent capabilities of refractory carbide materials of interest for this project.

References

1. J. Heremans and C.P. Beetz, Jr. Phys. Rev. B 32 p.1981 (1985).
2. A. Oberlin, M. Endo, and T. Koyama, J. Cryst. Growth, 32, 335 (1976).
3. A. Oberlin, M. Endo, and T. Koyama, Carbon, 14, 133 (1976).
4. B. Nysten and J.-P. Issi, Composite, 21, 339 (1990).
5. J.-M. Ting and M.L. Lake, pp. 269-88 in the Proceeding of the 16th Conference on Metal Matrix, Carbon, and Ceramic Composites, Cocoa Beach, FL, January, 1992.
6. J.-M. Ting and M.L. Lake, Final Report, Contract No. F33615-92-C-2240, October, 1992
7. J. -M. Ting and M. L. Lake, "Refractory Metal Coatings on Carbon/Carbon Composites for First Wall Applications," Final Report, Contract DEFG02-90-ER80886, July 1993.
8. R. T. K. Baker and P. S. Harris, "Chemistry and Physics of Carbon," p 83, Dekker, New York (1978).
9. Y. S. Touloukian, Editor, *The Thermophysical Properties of High Temperature Solid Materials*, Thermophysical Properties Research Center, Purdue University, sponsored by Air Force Materials Laboratory, MacMillan Company, New York, 1965.
10. E. K. Storms, *The Refractory Carbides*, New York, Academic Press, 1967.

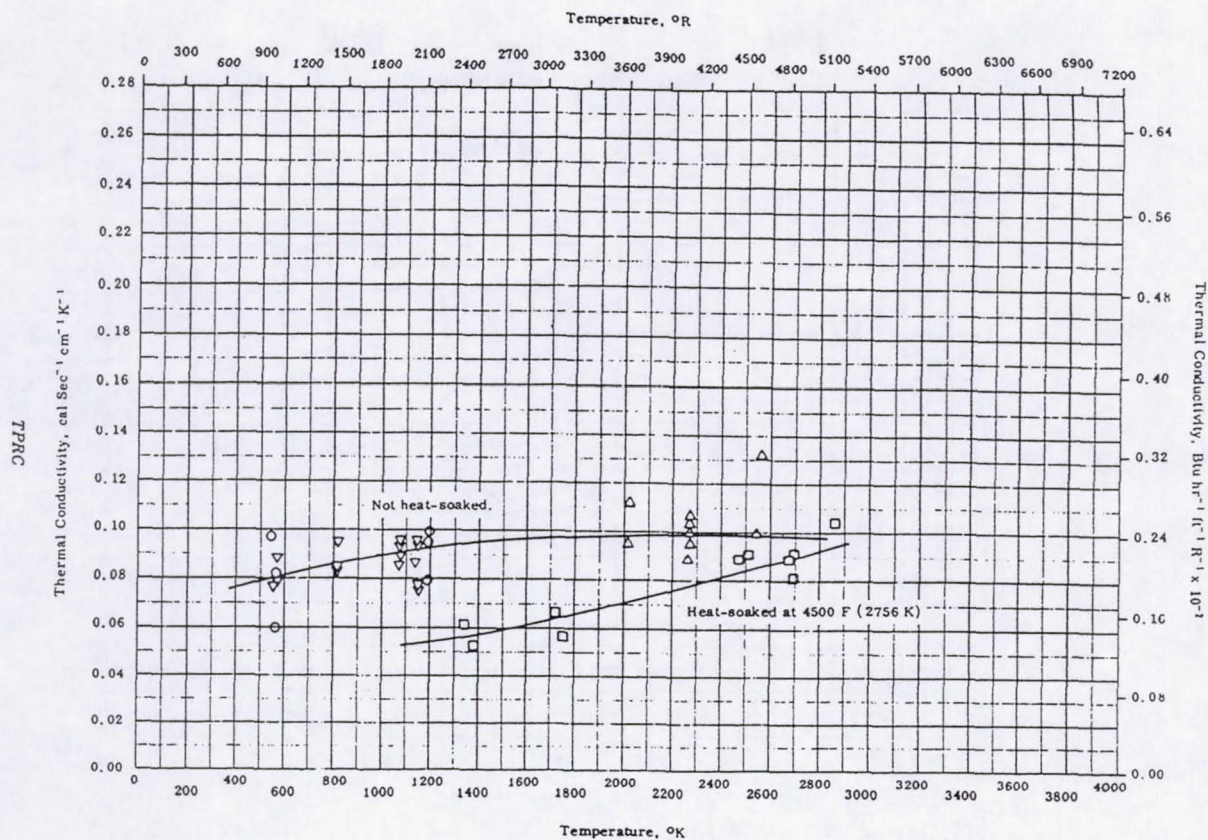


Figure 4.9. Thermal Conductivity of Tantalum Carbide.

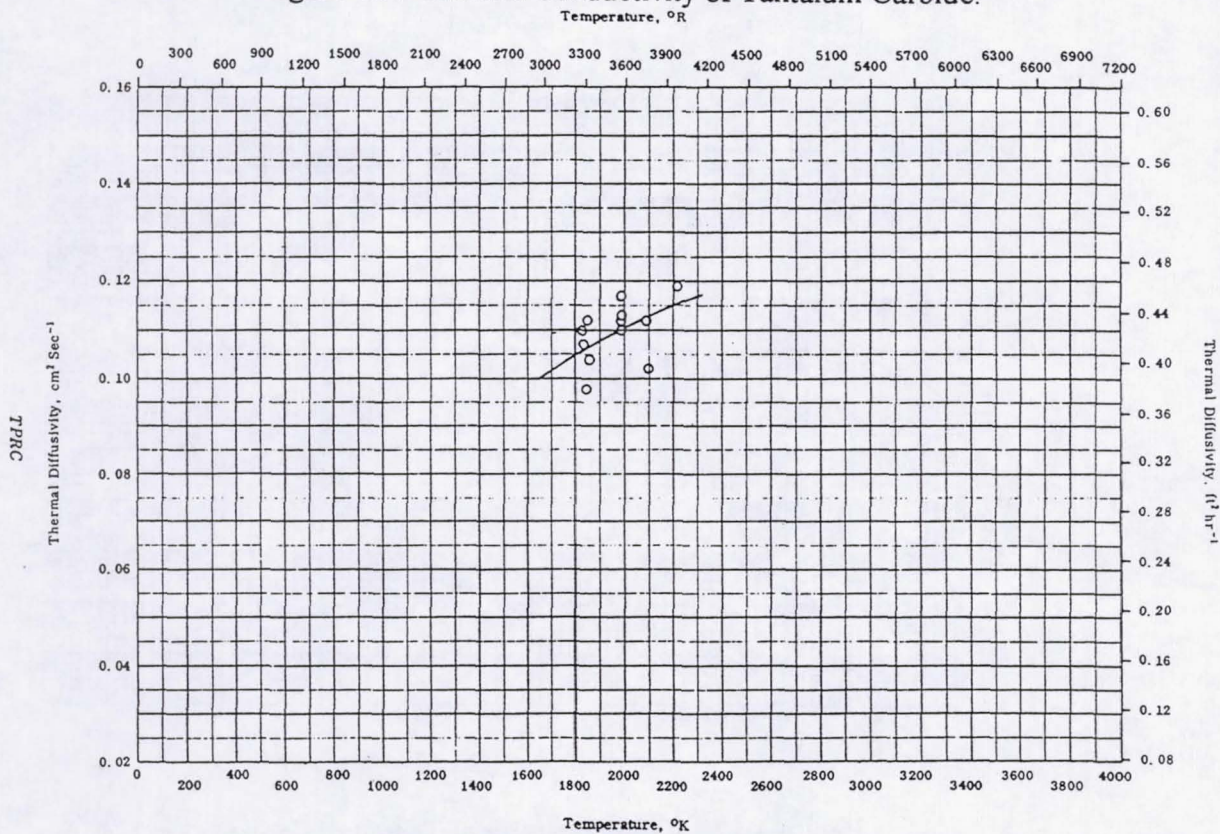


Figure 4.10. Thermal Diffusivity of Tantalum Carbide.

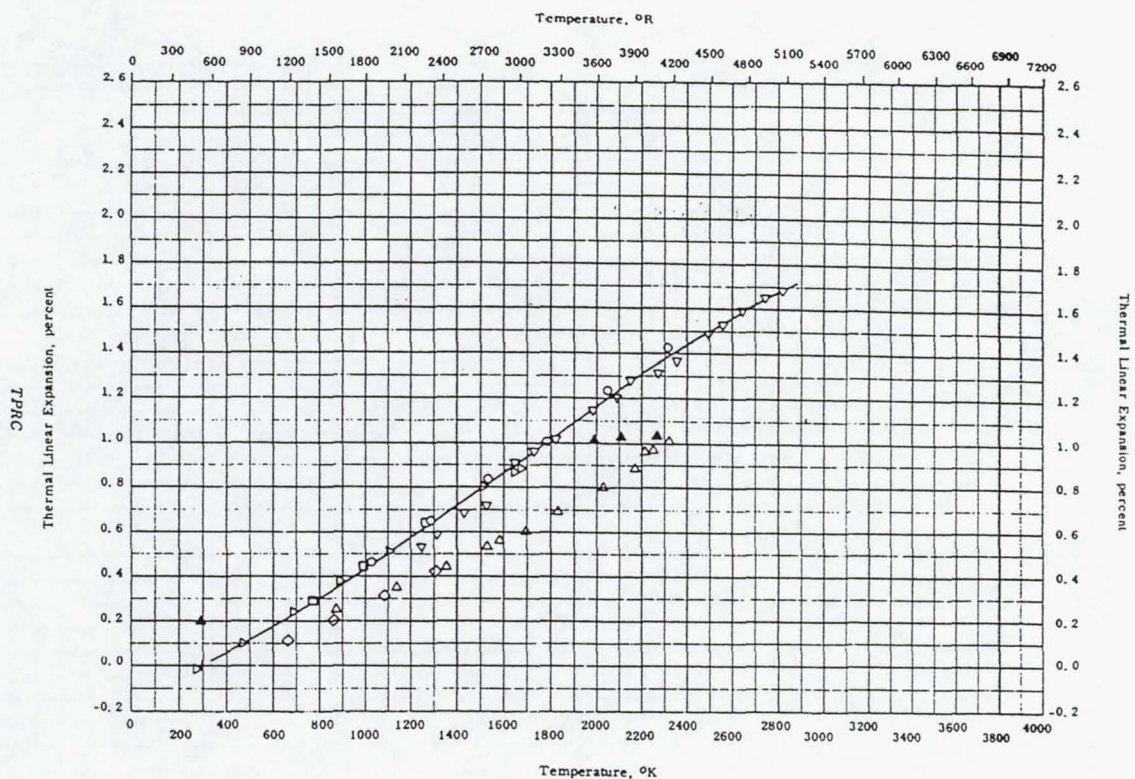


Figure 4.11. Thermal Linear Expansion of Tantalum Carbide.

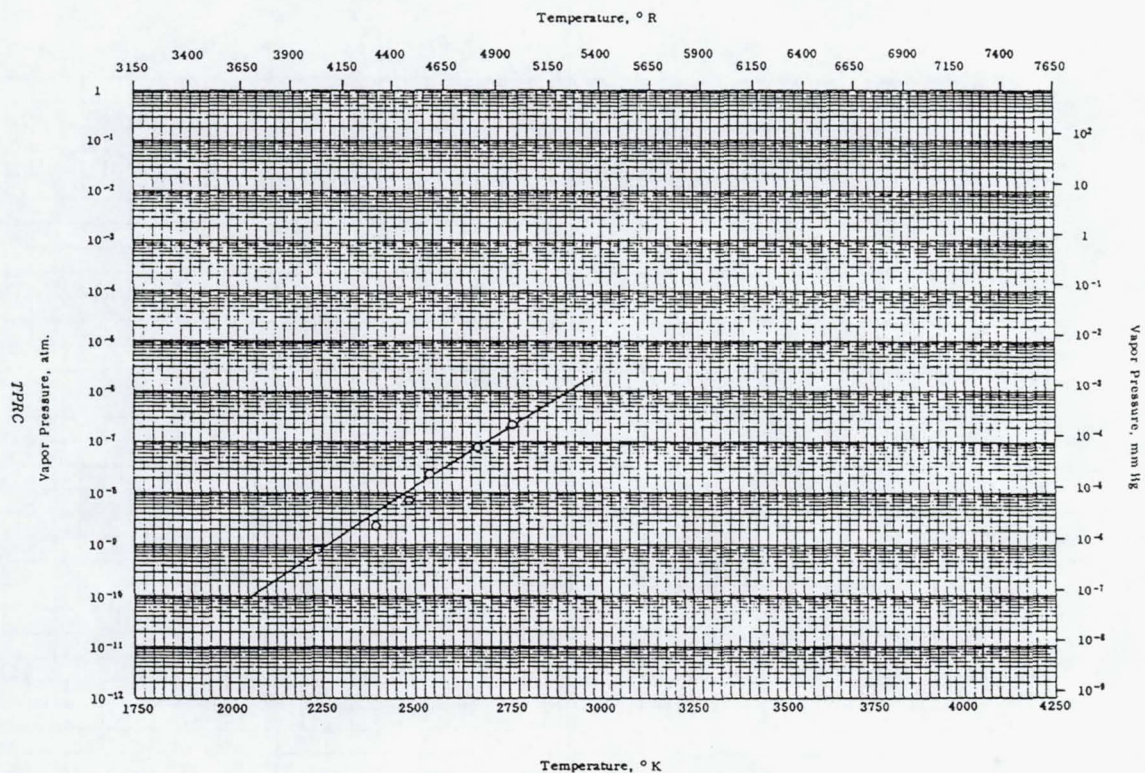


Figure 4.12. Vapor Pressure of Tantalum Carbide.

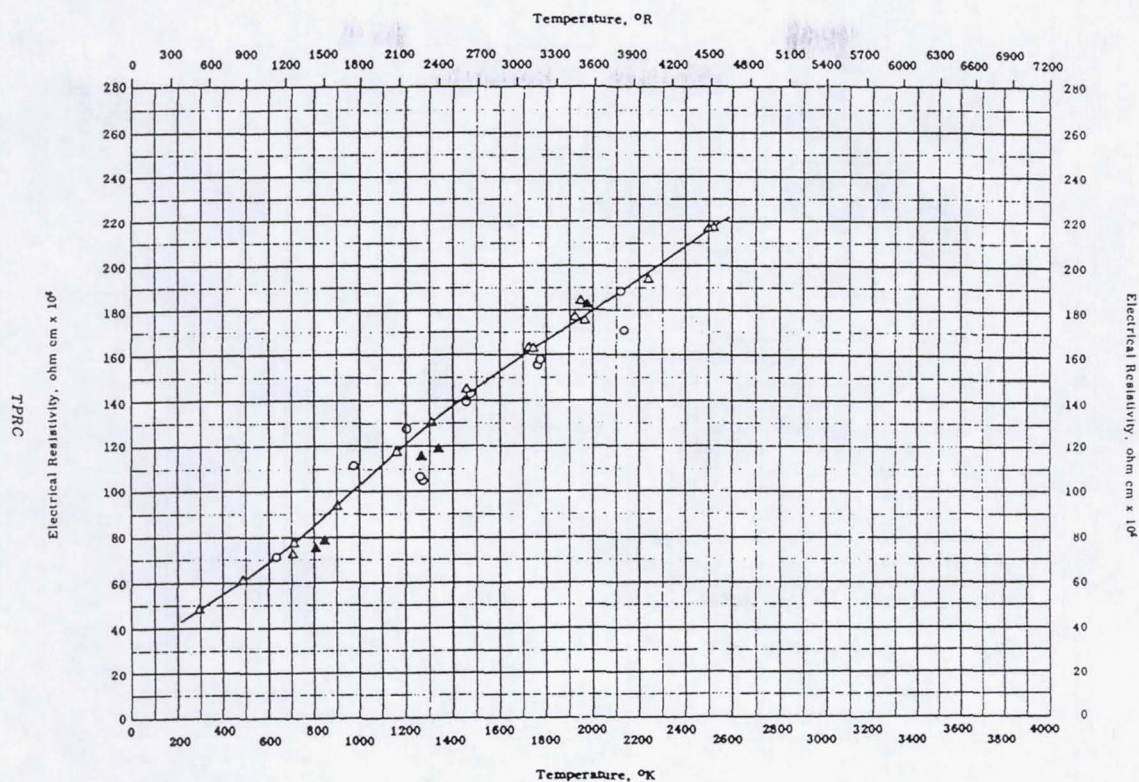


Figure 4.13. Electrical Resistivity of Hafnium Carbide.

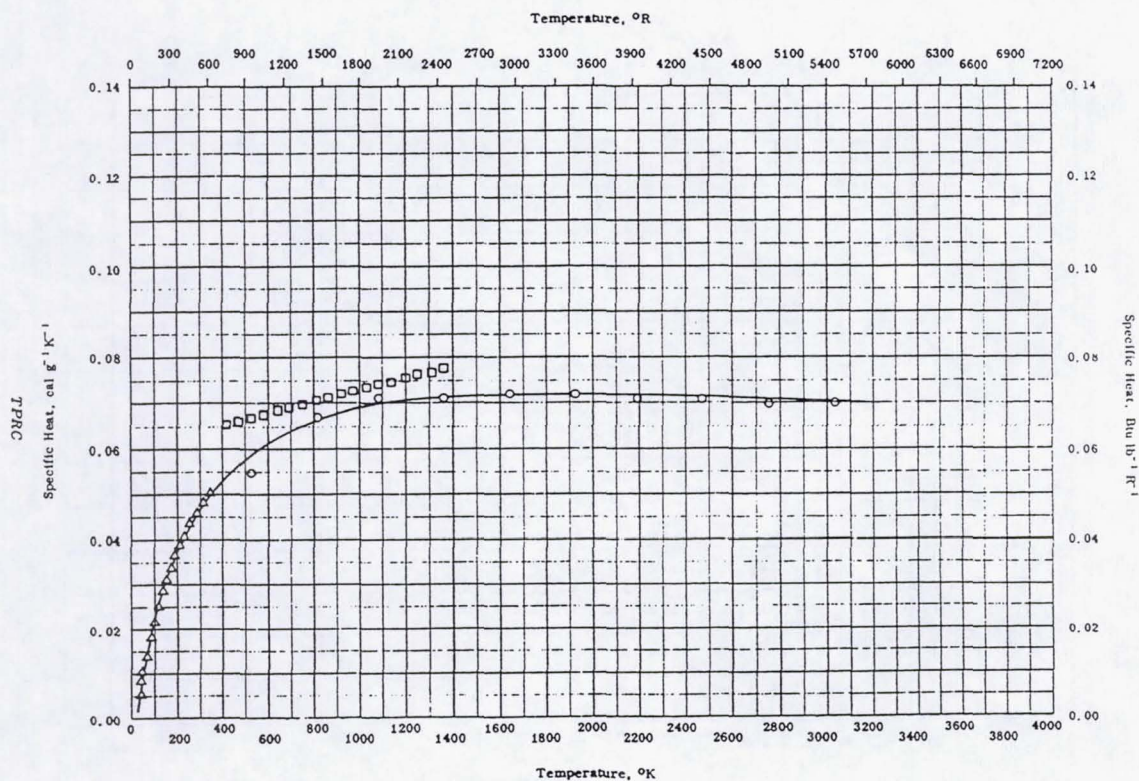


Figure 4.14. Specific Heat of Hafnium Carbide.

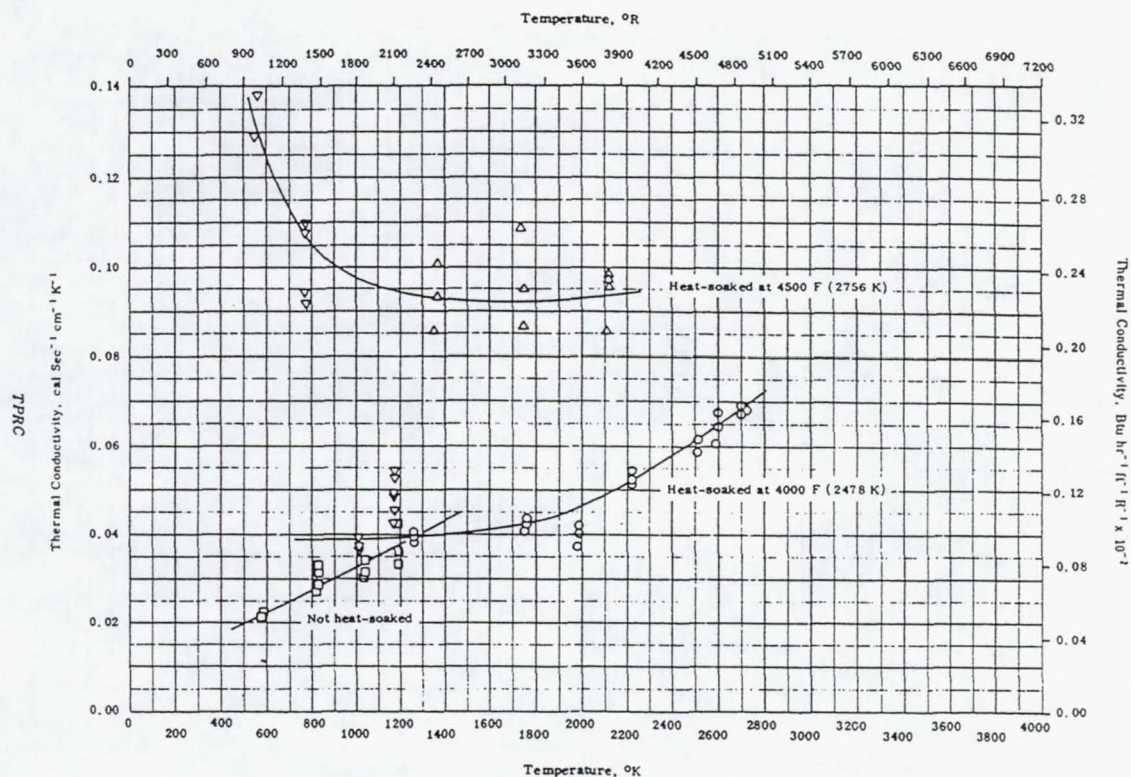


Figure 4.15. Thermal Conductivity of Hafnium Carbide.

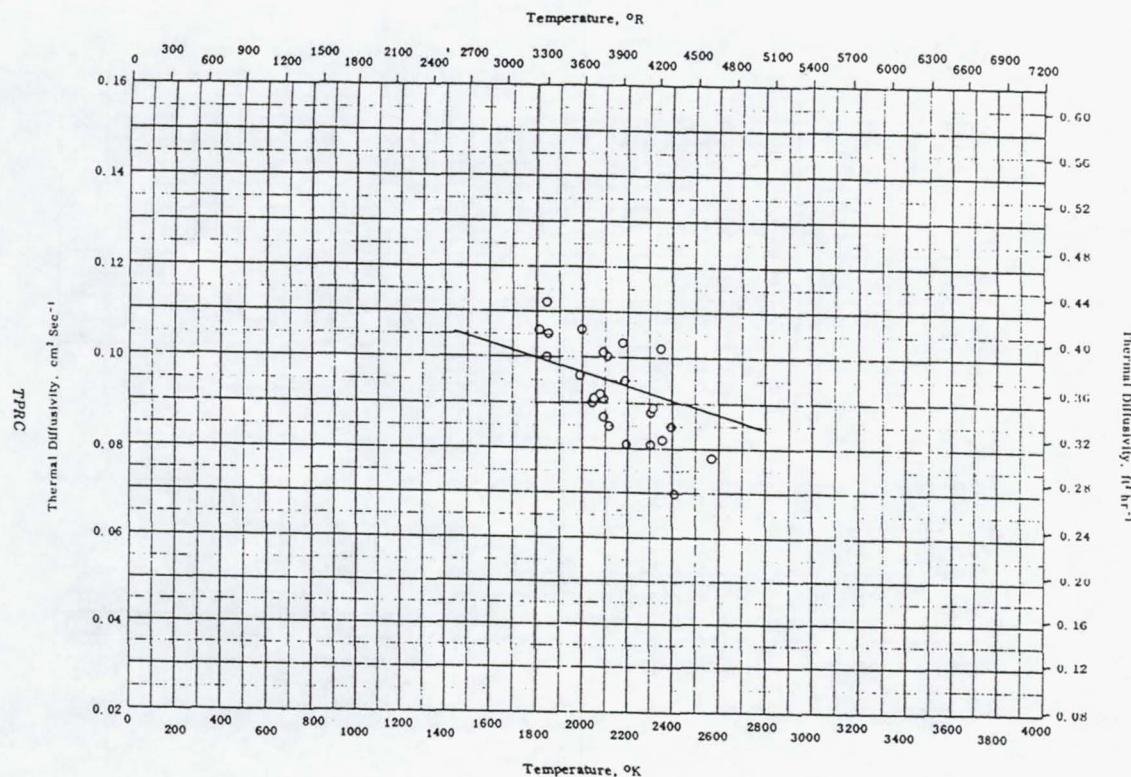


Figure 4.16. Thermal Diffusivity of Hafnium Carbide.

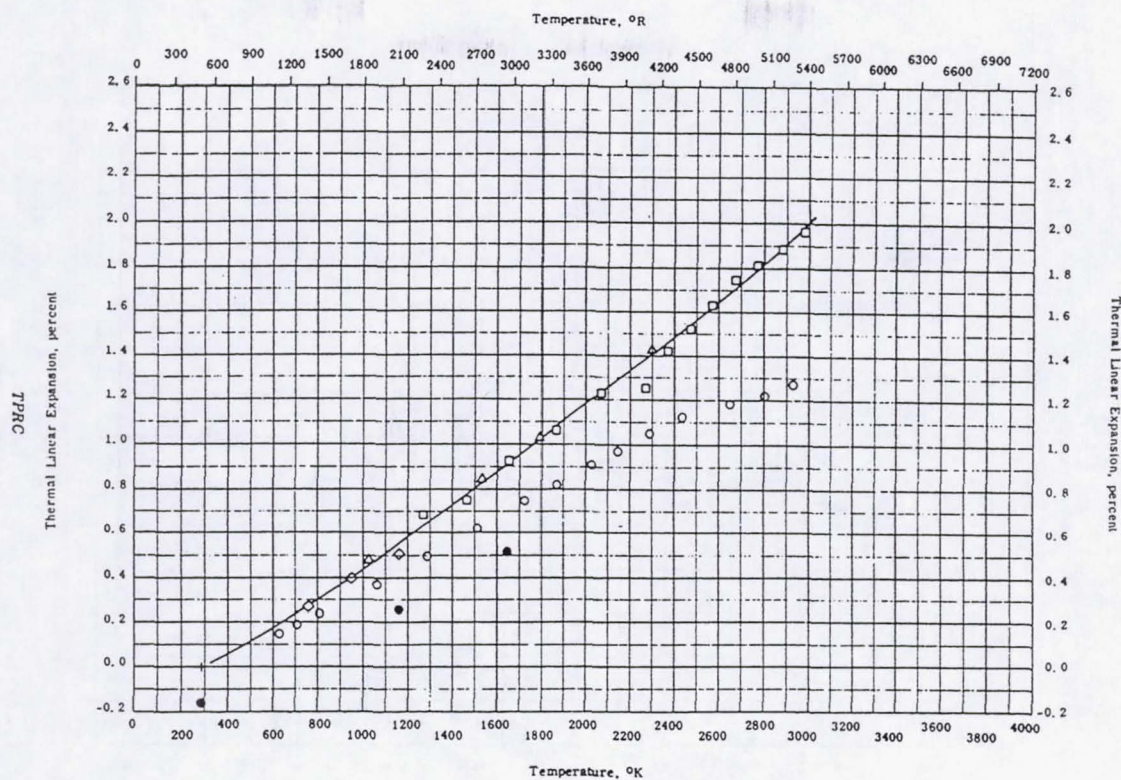


Figure 4.17. Thermal Linear Expansion of Hafnium Carbide.

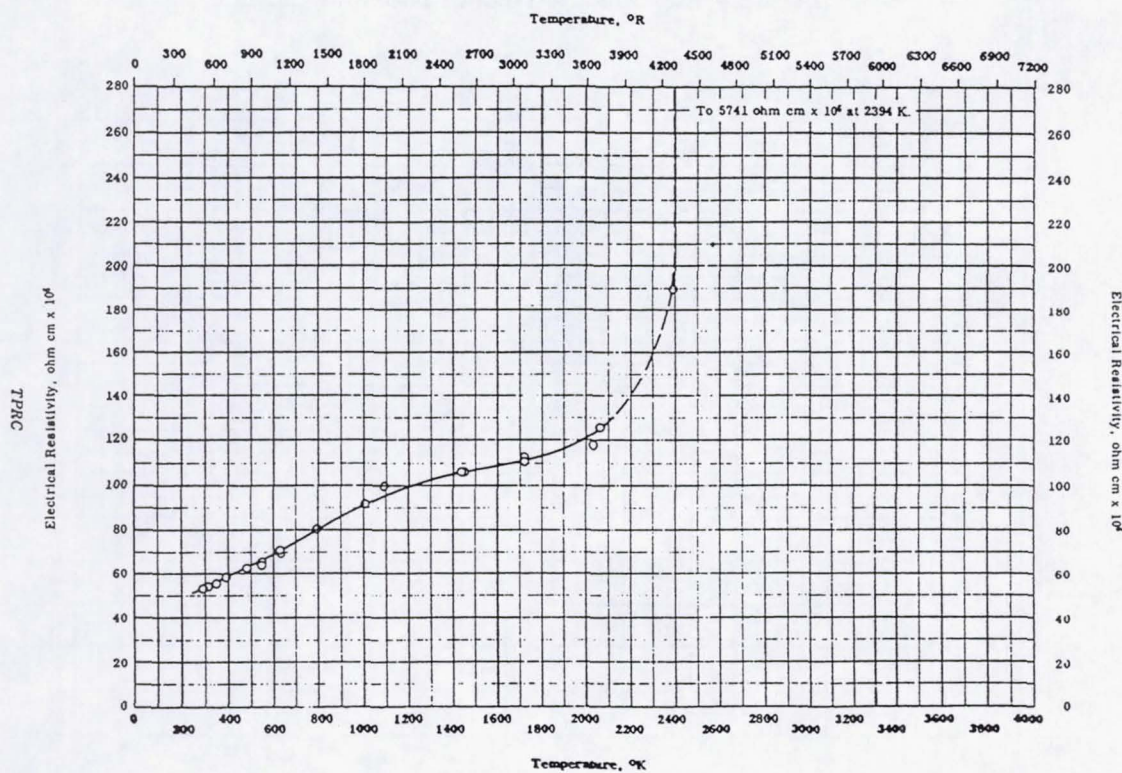


Figure 4.18. Electrical Resistivity of Niobium Carbide.

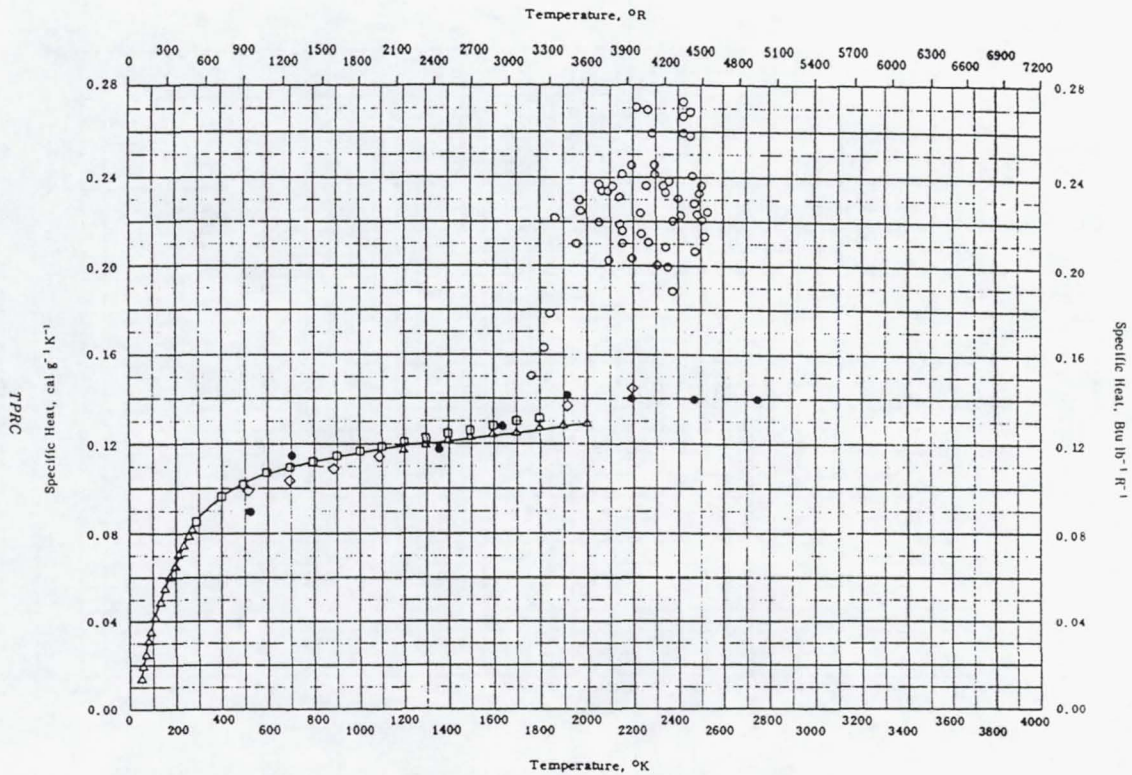


Figure 4.19. Specific Heat of Niobium Carbide.

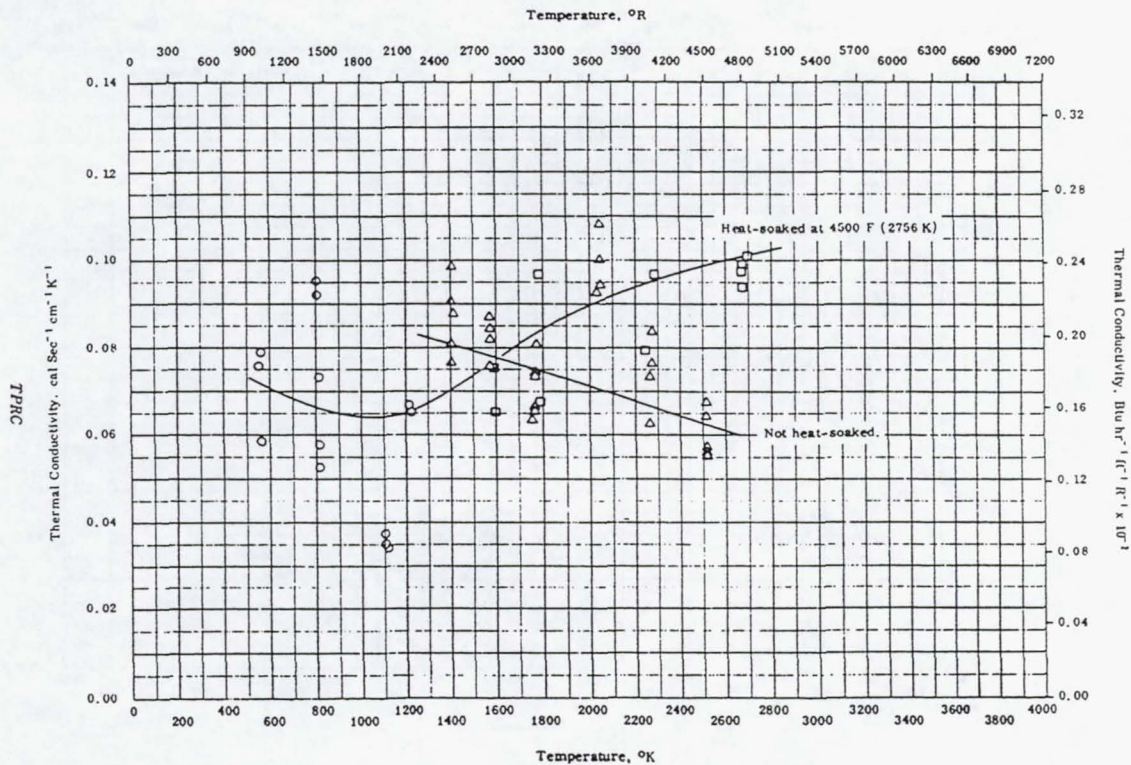


Figure 4.20. Thermal Conductivity of Niobium Carbide.

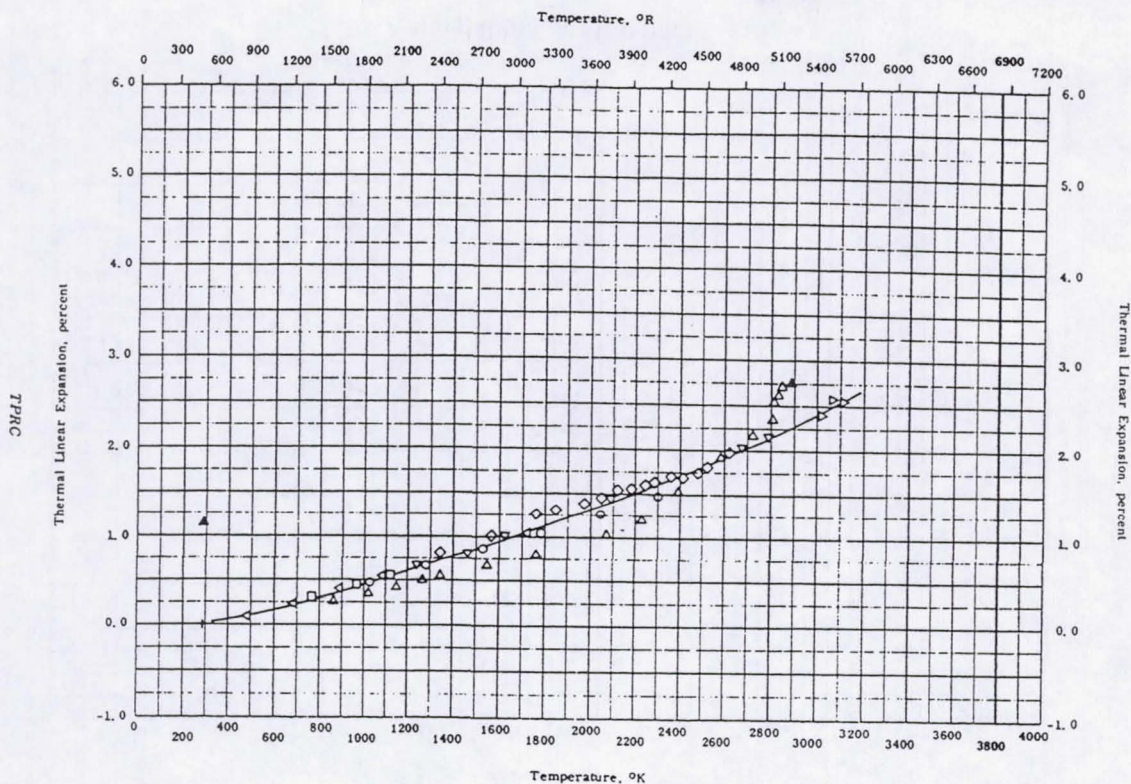


Figure 4.21. Thermal Linear Expansion of Niobium Carbide.

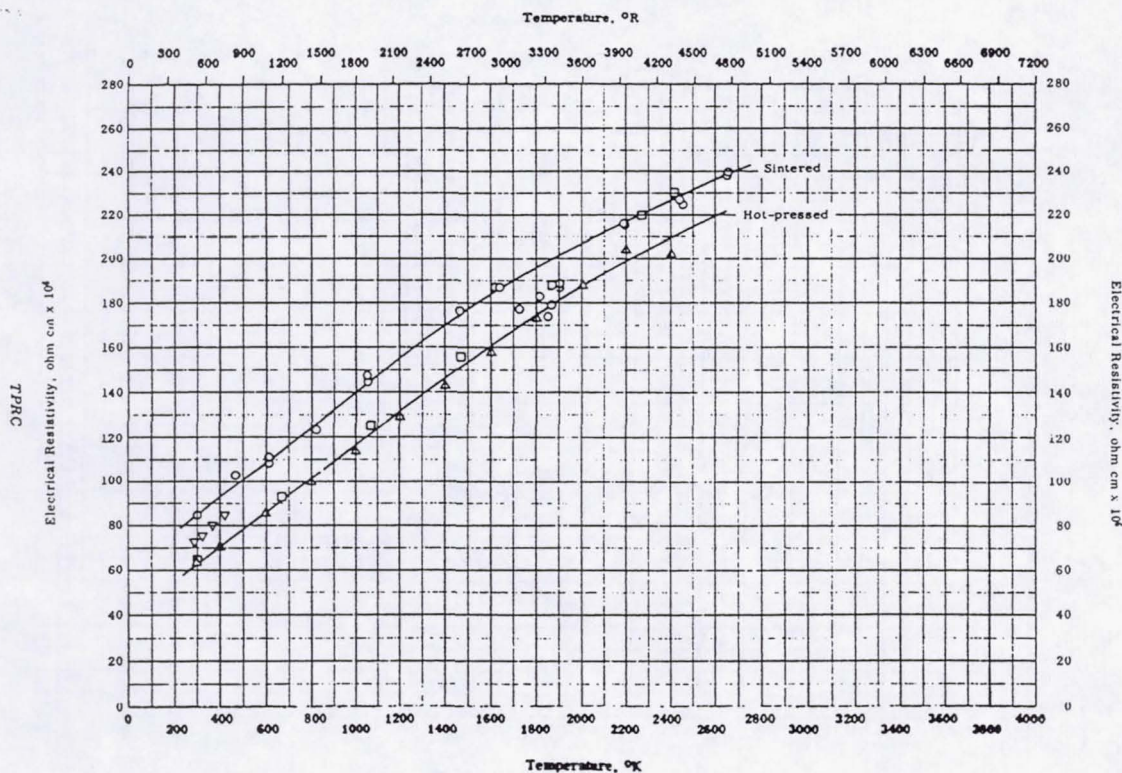


Figure 4.22. Electrical Resistivity of Zirconium Carbide.

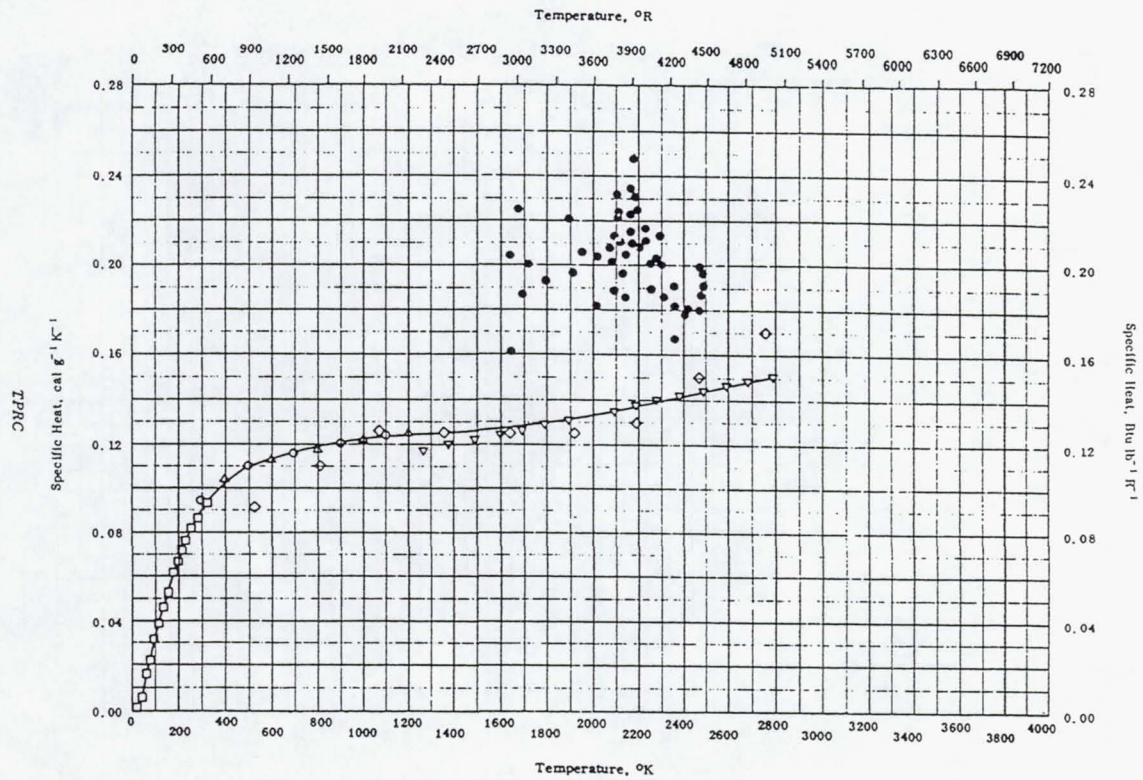


Figure 4.23. Specific Heat of Zirconium Carbide.

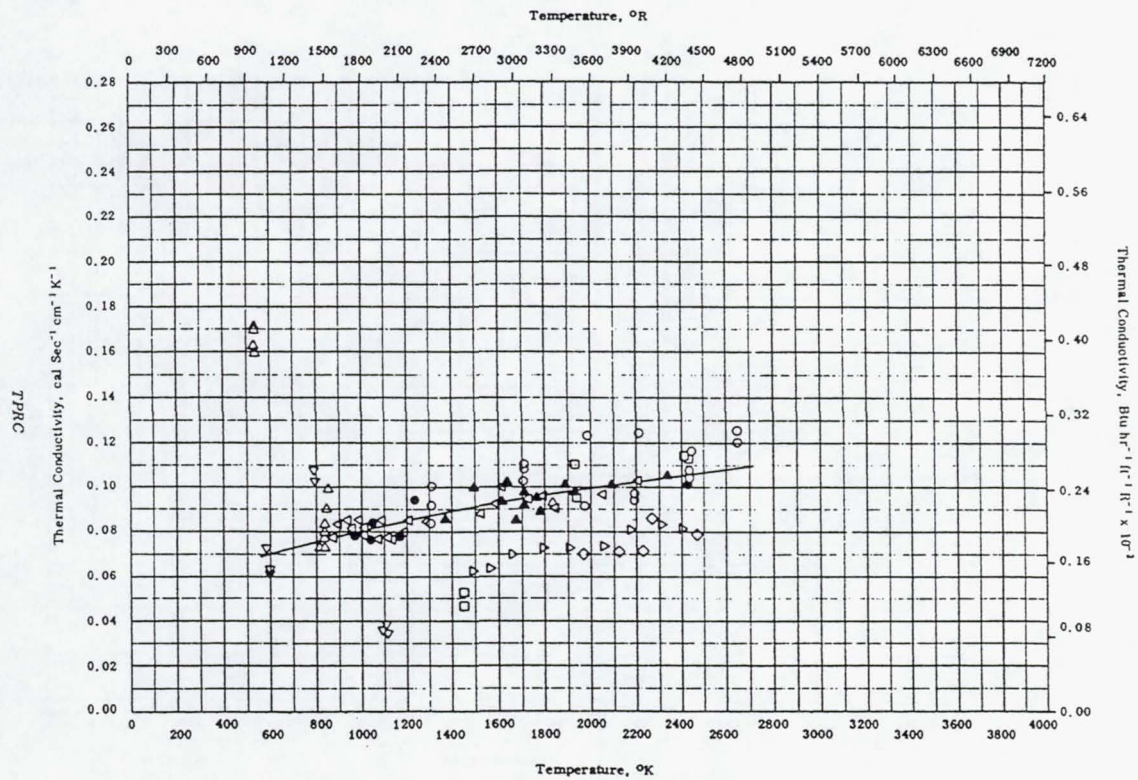


Figure 4.24. Thermal Conductivity of Zirconium Carbide.

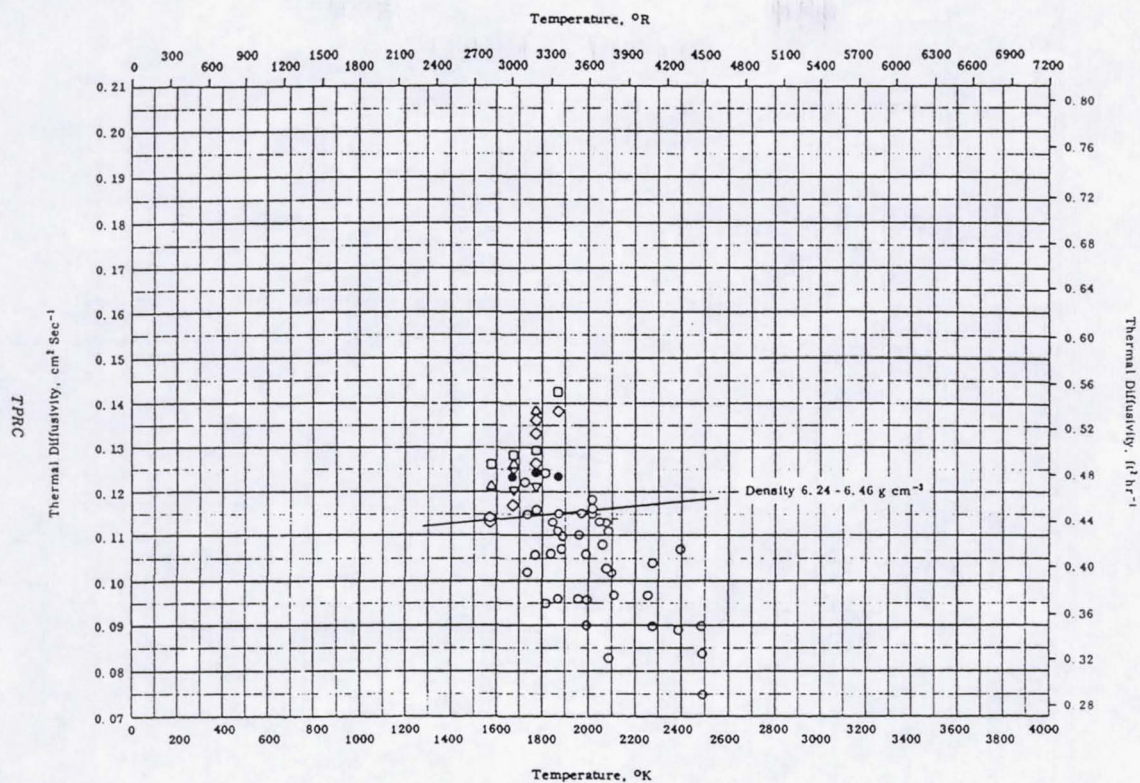


Figure 4.25. Thermal Diffusivity of Zirconium Carbide.

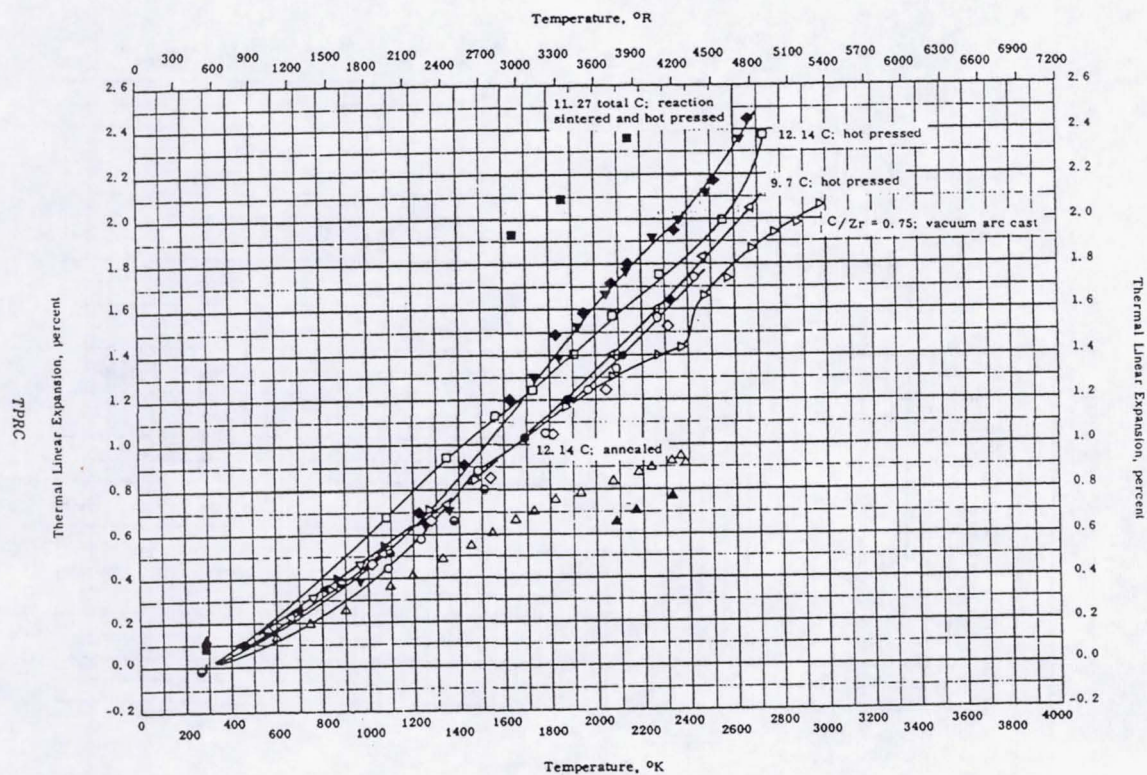


Figure 4.26. Thermal Linear Expansion of Zirconium Carbide.

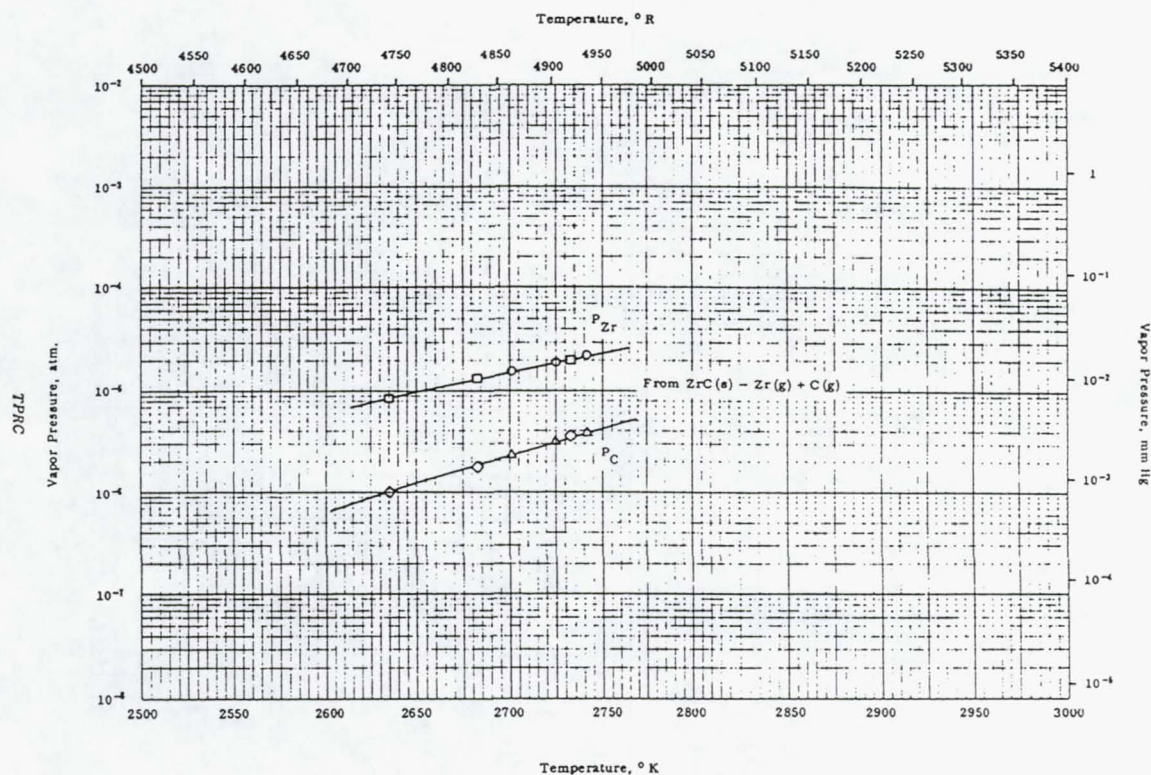


Figure 4.27. Vapor Pressure of Zirconium Carbide.

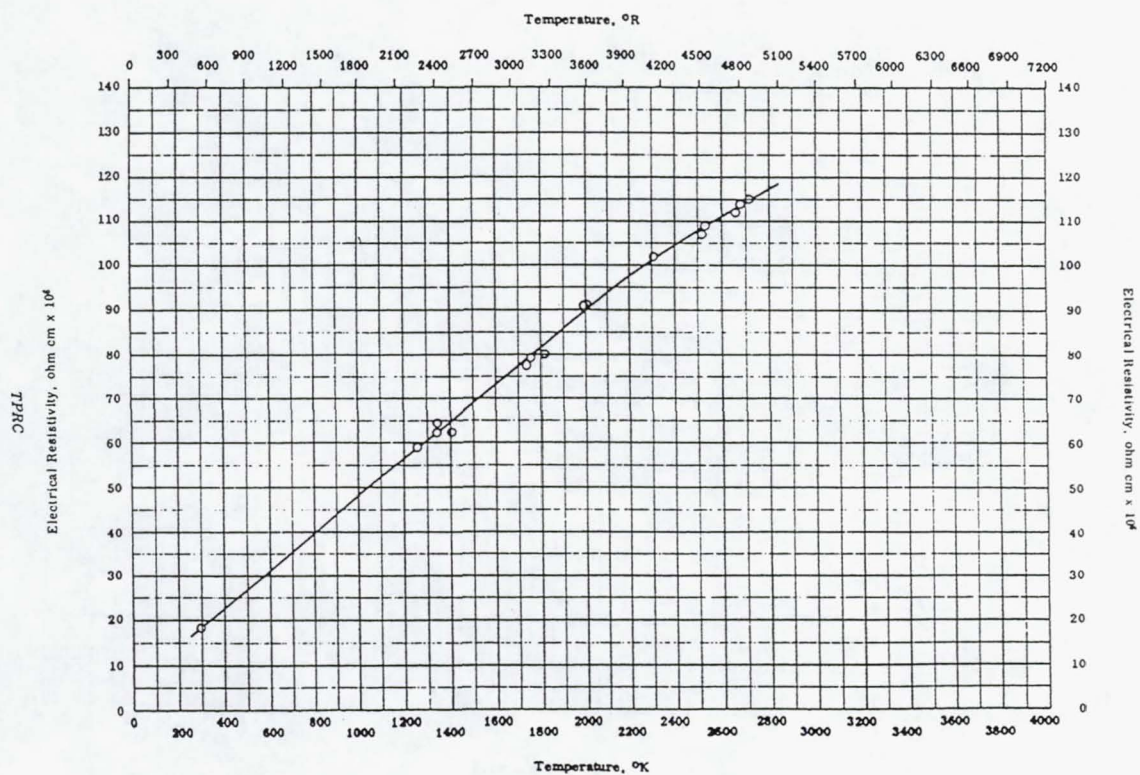


Figure 4.28. Electrical Resistivity of Tantalum Carbide.

V. INTERCHANGES WITH SCIENTIFIC PRODUCTION ORGANIZATION LUCH (NPO LUCH), RESEARCH CENTER ISTOK (NTTs ISTOK) AND THE SCIENTIFIC RESEARCH INSTITUTE OF THERMAL PROCESSES (NIITP)

The purpose of recounting the mechanics of our dealings with Russian entities is to allow our experience to benefit other US companies and institutes wishing to deal with Russia.

Dealings with Russian entities relevant to the performance of this contract consisted of three major functions: visit of the PI, Elliot Kennel to visit Russian facilities to determine the potential for interactions (accomplished during the pre-proposal phase and hence not an expense incurred under this contract); contracting with NPO Luch and its associated export firm NTTs Istok; and working with Dr. Alexey Nikolayevich Ivanov from NIITP.

In our original proposal we had intended to interface more strongly with NIITP and not with NPO Luch/NTTs Istok; however during negotiations it was decided to attempt to exploit the use of single crystal refractory metals, which necessitated a connection with NPO Luch/NTTs Istok.

The use of foreign technologists is something which Space Exploration Associates has done previously and can now be considered routine. Basically, this involves getting permission from Russian authorities to temporarily release an individual from his normal job duties, and hiring the individual as a part time employee.

Importing material (in this case, an ingot of single crystal tungsten-tantalum alloy) is a more involved process. Because this experience may be repeated by other NASA contractors, we believe that it would be useful to review the process in detail to facilitate the purchase of similar items in the future.

First, the time of the initiation of our contract (25 October 1993) to the time we took possession of the material (18 August 1994) was nearly ten months. This despite the fact that we had already determined what we wanted to buy by July 1993. This long delay was caused by a combination of political factors on the US and Russian sides. Our purpose in recounting these difficulties is not to cast blame on one side or the other, but to recount the factors that must be satisfied for a successful, legal import of Russian materials to the United States. Entities wishing to do business with Russian institutes should not be astonished to find that the bureaucracies of the two nations are very formidable.

We first considered whether we should have the machining done in Russia, or whether it should be done in the US. The machining services are less expensive in Russia, and furthermore the Russians obviously have more experience in machining this material than Americans. However, we were told that this would vastly complicate the import process on the US end, because the material would now be considered an aerospace component, subject to much tighter restrictions. We were told that it was not impossible to be granted a waiver, but State, Commerce, and the Bureau of Tobacco and Firearms would be involved. On the other hand, if the ingot were sent unmachined, it be simpler to declare through Customs. We elected to follow this route.

Incidentally, our corporate experience has generally been very favorable with persons from the State Department, Commerce Department and Bureau of Tobacco and Firearms. These individuals really do want to be helpful to US companies wishing to deal

with foreign entities (an exception to this, early in the formation of our company, was a bureaucrat at the State Department who once threatened to have the fax machine in our office--in Cedarville Ohio--declared a foreign weapon and impounded, since it might conceivably receive weapon information from Russia. We never called this gentleman back, and so far our fax machine is continuing to operate without an import license. No atomic bomb or other military secrets have been revealed to us so far, either). In general, our experience has been that as long as we tell the government agencies in advance what we want to do, they are almost always very helpful to us. However, they also tell us that what they do not appreciate is when US companies do something first and tell them later, and we have attempted to comply with this reasonable request.

At any rate, once deciding to attempt to import an ingot of W-Ta alloy, we were told by letter from NPO Luch/NTTs Istok that a signed contract would be required in order to place an order. We attempted to satisfy this requirement in early November by placing a signed Purchase Order together with a signed letter indicating our intent to purchase the item. We thought that this fulfilled the requirements on the Russian side, but we were mistaken.

During a meeting with Yuri Nikolayev in Washington in December, this was made clear. A formal contract would issue from the Russian side for our review. This was transmitted to us via telefax in late January, translated and signed in February 1994. Obviously, the Luch people used some other contract as a model (note that on page one, Space Exploration Associates is referred to as "being a legal entity according to the legislature of *Japan*") However, we elected not to contest this or any of the other language of the document in the interest of saving time. From our point of view, it was not necessary to have such a contract, but if it was required on the Russian side, we were willing to sign it. Note: translation of an eight page legal contract can be extremely expensive for most US companies. The actual contract plus English translation is contained in Appendix I of this report in hopes that it may be useful to other NASA entities wishing to do business with Russian business entities.

We were told that it would take four months from the time of signing the contract to the time of delivery of the item. In actuality it took six months. We do not know the reason for the long time of delivery. We doubt that there is a problem with back-orders. The actual time to fabricate a specimen is likewise presumed to be short. It can be assumed that paperwork processing is the most time consuming element in the process.

Clearing the item through customs took one week. We had to contract with a broken, Schenker International of Columbus, Ohio, to extract the item from US Customs. The Customs fees resulted in a cost overrun of about \$3000.

Thus for companies wishing to estimate the costs of purchasing similar materials from Russia, we recommend that about 30% extra be added to the price. However, this cost should go down on repeat orders, since the procedure will become established, and so less preparation will be required on the part of the US contractor.

Some individuals (who will remain anonymous here for obvious reasons) have pointed out that it is possible to deceive US customs by declaring a lower purchase price--for items less than ~\$1000, it is often possible to take possession directly. However, the Space Exploration Associates company policy must obviously be to do business fairly, properly and legally within the frameworks of both the US and Russian government. We

recommend against deceptive importing procedures, which are after all quite illegal. Therefore, our suggestion is that a factor of ~30% additional cost for customs declarations and fees and paperwork processing (labor) on the US side is probably typical for raw materials of this sort. Finished hardware will probably be even more expensive and probably more difficult to obtain proper permission to import.

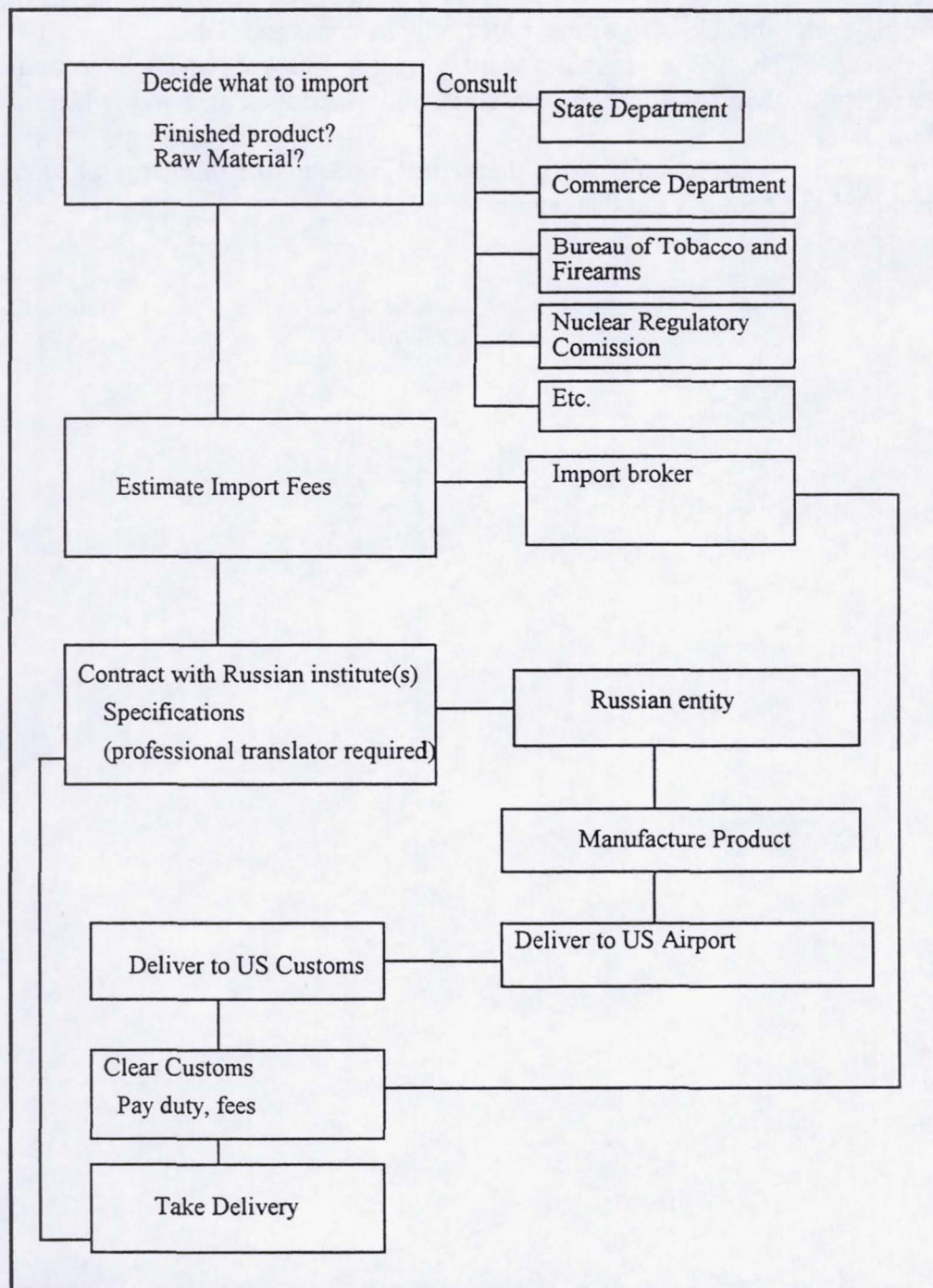


Figure 5.1 Simplified "Wiring Diagram" for Import of Russian Materials

As far as sponsoring the visit of Russian nationals to work as temporary hires is concerned, we found this to be much simpler, having had similar arrangements in the past with NPO Luch and other Russian and Georgian entities.

Dr. Alexey Nikolayevich Ivanov visited Space Exploration Associates for a period of two months, using an H-1B visa. This is merely a question of filling out the appropriate forms from the US Department of Immigrations and Ohio Bureau of Employment Services. This was a straightforward process, and one which is recommended as an excellent method for supporting international exchanges in a way which is beneficial to both sides.

Dr. Ivanov contributed a theoretical modeling of discharge phenomena which is included as Chapter VI in this report.

VI. TIME DEPENDENT ELECTRON ENERGY DISTRIBUTION IN A SLIGHTLY IONIZED ATOMIC GAS

1. Introduction

This chapter, contributed by Dr. Alexey N. Ivanov of NIITP, analyzes the electron energy distribution in a plasma. This is peripherally related to the design of arcjet thrusters and other problems involving plasma electrical discharges.

In many physical problems it is necessary to know the time evolution of an electron energy distribution function (EEDF). This reveals additional information about the properties of plasma generated by a beam of ionized and neutral particles. The characteristics of this plasma beam such as rates of plasmachemical reactions, conductivity, dielectric permittivity and others may vary significantly in time.

Calculations of time dependent electron energy distribution functions have been fulfilled for argon and xenon plasmas.¹ Detailed numerical calculations of degradation spectra of electrons have been recently performed for atomic nitrogen, atomic oxygen and molecular nitrogen.^{2,3,4,5}

These formulas describing degradation spectra of electrons for moderate energy ($E > 200$ eV) have been derived for the problem of the establishment of steady state conditions after initiation of an electron source, and the concomitant problem of relaxation phenomena.

2. The time dependent equation of the degradation spectrum of electrons in an atomic gas.

We begin by considering a uniform atomic gas with uniformly distributed isotropic sources of primary electrons, producing slightly ionized plasma. This situation occurs, for example, in fissionable gas plasmas. The initial energy of electrons E_0 is assumed to be less than 10 MeV when electron losses for brehmstrahlung are disregarded. The extent of ionization is assumed to be small so that electron-electron (e-e), electron-ion (e-i) and de-excitation collisions may be neglected also.

Then the equation of degradation spectrum may be written as^{6,7}:

$$\frac{\partial n}{\partial t} = -\frac{\partial}{\partial E} \left(n \frac{dE}{d\tau} \right) + Q(E, t) \quad (1)$$

where $n = n(E, t)$ is the electric energy distribution function, $\frac{dE}{d\tau}$ is the average energy deposition rate and $Q(E, t)$ is the rate of electron production density per unit volume.

The quantity $\frac{dE}{d\tau}$ is a function of the energy E and has to be determined in advance. When $E \gg I$, where I is the atom ionization potential, the relaxation equation is valid,

$$\frac{dE}{d\tau} = -Nv(E) \sum_i \sigma_i(E) E_i \quad (2)$$

where N is the atom density, $v(E)$ is the velocity of electrons with energy E , $\sigma_i(E)$ is the cross section of the i th process of electron-atom interactions and E_i is the average energy lost by electrons in the i th process.

In a wide range of energies from $\mu_0 = 0.1$ eV up to E_0 the value may be determined by the Monte Carlo method.⁶

The function $\frac{dE}{d\tau}$ for helium is shown in Figure 1. The shape of this curve is typical for all atomic gasses.

Thus $\frac{dE}{d\tau}$ is an important value for further evaluation and is a function of energy E only:

$$\frac{dE}{d\tau} = P(E) \quad (3)$$

By introducing the new notation

$$f(E, t) = n(E, t) P(E)$$

Equation (1) can be rewritten as

$$\frac{\partial f}{\partial t} + P(E) \frac{\partial f}{\partial E} = P(E) Q(E, t) \quad (4)$$

The analytical solution of this equation is

$$f(E, t) = \int_{E_0}^E Q(E', t - \tau(E) + \tau(E')) dE' + F(t - \tau(E)) \quad (5)$$

where $\tau(E)$ is the solution to Equation (3) with an initial condition $\tau(E_0) = 0$. This dependence for helium is shown in Figure 2. The specific form of $F(t - \tau(E))$ must be determined from the initial conditions.

3. The establishment of steady state.

For steady state, the initial condition is $f(E, 0) = 0$ and Equation (5) converts to:

$$f(E, t) = \int_{E(\tau(E)-t)}^E Q(E', t - \tau(E) + \tau(E')) dE' \quad (6)$$

where $E(\tau)$ is the inverse function of $\tau(E)$.

Because the specific form of the source term is difficult to evaluate, we have considered first the high energy regime of the degradation spectrum $E \gg I$. In this case we have been able to ignore the contribution of secondary electrons in $Q(E,t)$ because these electrons have been produced with less than 100 eV, and so

$$Q(E,t) = S(E)\theta(t) \quad ,$$

where $S(E)$ is the density of primary electron production and $\theta(t)$ is Heaviside's function. Thus the solution of Equation (1) can be written as:

$$f(E,t) = \int_{E[\tau(E)-t]}^E S(E')\theta(t - \tau(E) + \tau(E'))dE' = \int_{E[\tau(E)-t]}^E S(E')dE' \quad , \quad (7)$$

with

$$n(E,t) = \frac{1}{P(E)} \int_{E[\tau(E)-t]}^E S(E')dE' \quad .$$

When $E \gg I$, Equation (2) is valid and finally we have

$$n(E,t) = \frac{1}{Nv(E) \sum_i \sigma_i(E) E_i} \int_E^{E[\tau(E)-t]} S(E')dE' \quad (8)$$

The establishment of steady state requires a time $t \sim \tau(E)$. The steady state is described by

$$n_{ss}(E,t) = \frac{1}{Nv(E) \sum_i \sigma_i(E) E_i} \int_E^{E_0} S(E')dE' \quad (9)$$

This result coincides with a stationary distribution deduced from a model of continuous slowing of electrons.^{7,8}

4. Relaxation of the stationary degradation spectrum

In this case in the high energy tail of the degradation spectrum, Equation (1) can be simplified to

$$\frac{\partial n}{\partial t} = -\frac{\partial}{\partial E} \left(n \frac{dE}{d\tau} \right) \quad (10)$$

Taking into account the initial condition $n(E,0) = n_{ss}(E)$,

$$n(E, t) = \frac{1}{Nv(E) \sum_i \sigma_i(E) E_i} \int_E^{E_0} S(E') dE' \quad (11)$$

The typical time of relaxation of steady state in the vicinity of energy E appears to be the same as the time for the establishment of steady state. Evidently, this is a consequence of the linearity of Equation (1).

5. Conclusions.

The main results are as follows:

1. The analytical solution of the time dependent equation of the degradation spectrum has been obtained.
2. In the high energy tail of the degradation spectrum ($E \gg 200$ eV) we have obtained convenient formulae describing the establishment of steady state and the relaxation of the stationary degradation spectrum.
3. It has been shown that the establishment of a stationary degradation spectrum in the vicinity of energy $E \gg I$ requires a time $t \sim \tau(E)$. The same time is needed for the relaxation of steady state in the high energy regime.
4. The stationary solution of the equation of the degradation spectrum appears to coincide with the solution resulting from the model of continuous slowing down of electrons.

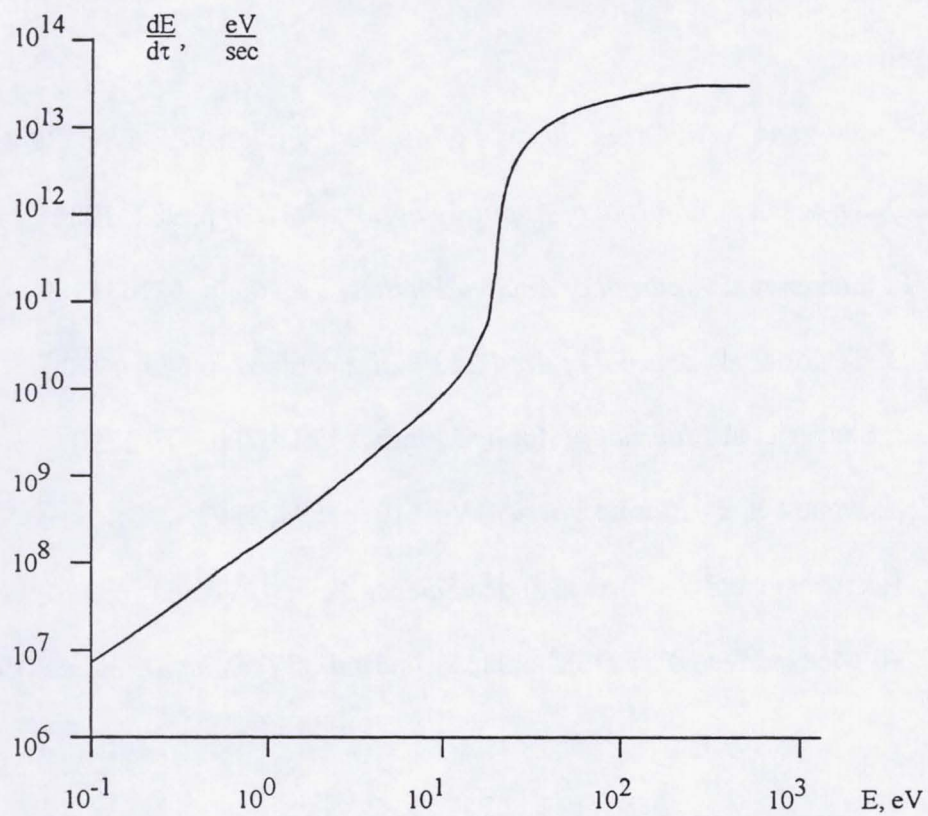


Figure 6.1. Energy deposition rate as a function of electron energy.

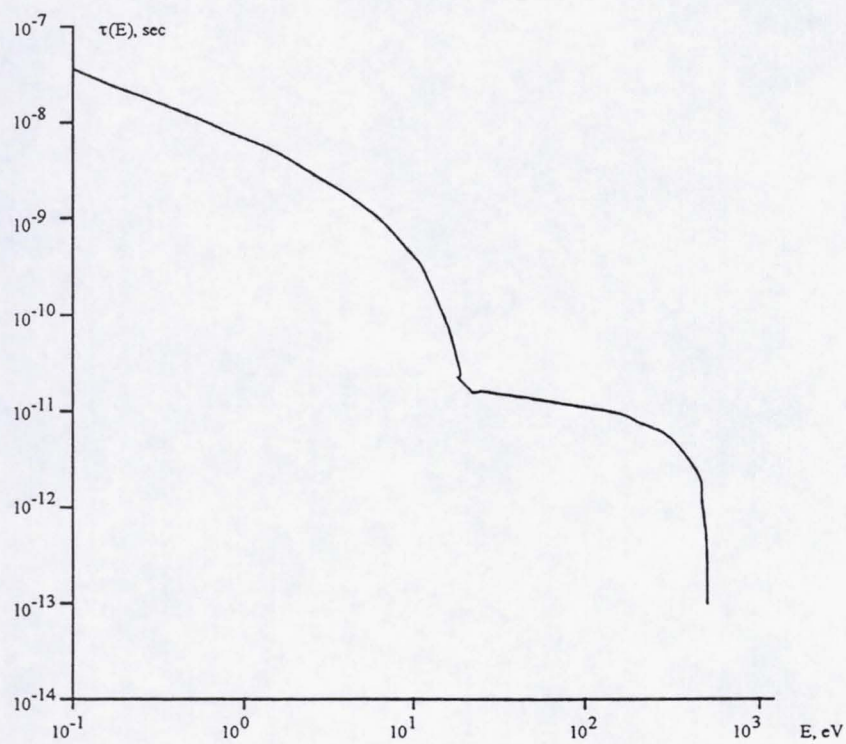


Figure 6.2. Relaxation time as a function of electron energy.

References.

1. C. J. Elliot and A. E. Green, *Journal of Applied Physics*, Vol. 47, p. 2946, 1976.
2. R. D. Taylor et al., *Journal of Applied Physics*, Vol. 64, p. 982, 1988.
3. S. P. Slinker et al., *Journal of Applied Physics*, Vol. 66, p. 5216, 1989.
4. R. D. Taylor et al., *Journal of Applied Physics*, Vol. 67, p. 679, 1990.
5. S. P. Slinker et al., *Journal of Applied Physics* Vol. 67, p. 679 1990.
6. A. N. Ivanov et al., *Plasma Physics*, Vol. 19, p. 594, 1993.
7. K. Takayanagi and Y. Itikawa, *Space Science Review*, Vol. 11, p. 380, 1970.
8. U. A. Medvedev and V. D. Khokhlov, *Journal of Technical Physics*, Vol. 49 p. 309, 1979.

VII. CONTRACT REPORTING REQUIREMENTS

1. Product Assurance Program Plan.

This effort is a research and development project. The hardware deliverable consists of a metal ingot, 3.5 cm diameter by 10 cm long, made from single crystal tungsten tantalum alloy which was fabricated under subcontract by the Scientific Research Center Istok/Scientific Production Organization Luch, in Podolsk, Russia. The specifications were prepared by the Project Engineer, Mr. Elliot Kennel.

2. Preliminary Hazards Analysis and Operating and Support Hazard Analysis.

The contract hardware deliverable consists of a metal ingot, 3.5 cm diameter by 10 cm long, made from single crystal tungsten tantalum alloy which was fabricated under subcontract by the Scientific Research Center Istok/Scientific Production Organization Luch, in Podolsk, Russia. This material is chemically inert, non-flammable and does not pose any hazard to the environment or to safety.

3. Failure Mode Effect and Criticality Analysis.

As this effort is research and development, these criteria do not apply.

VIII. CONCLUSION.

Ultimately, the success of this effort will be evaluated according to whether the materials discussed herein result in a superior arcjet or not. Thus, we will have to await test results to determine the ultimate success. However, there are several indicators which give good cause for optimism.

Fabrication of tungsten alloy single crystals in the sizes required for fabrication of an arcjet anode has been shown to be feasible. Test data indicate that the material can be expected to be at least the equal of W-Re-HfC polycrystalline alloy in terms of its tensile properties, and possibly superior.

We are also informed by NPO Luch that it is possible to use Russian technology to fabricate polycrystalline W-Re-HfC or other high strength alloys if desired. This is important because existing engines must rely on previously accumulated stocks of these materials, and a fabrication capability for future requirements is not assured.

The carbon composite materials technology appears up to the task of fabricating arcjet anodes as an alternative. However, whereas some NIITP designs employ a rotating arc to achieve high cathode performance and lifetime (but which places additional requirements for high thermal diffusivity at the anode), similar achievements have been made by optimizing the cathode thermal design for US arcjet thrusters. Accordingly, the motivation for pursuing a high thermal diffusivity anode is not obvious for US designs, and NIITP has thus far not been successful in supplying a performance rationale.

On the other hand, carbon materials may offer higher strength and creep resistance than refractory metal electrodes, which may be useful in its own right. Alternatively, if it is necessary to keep certain parts of the anode cool, the high thermal conductivity feature of carbon-carbon will represent enabling technology.

КОНТРАКТ № И-108 К

Научно-производственное объединение "Луч", являющееся юридическим лицом по законодательству Российской Федерации, действующее через свое отделение - НТЦ "Исток", именуемое в дальнейшем "Продавец", с одной стороны, и американская ассоциация "BRACE EXPLOATION ASSOCIATES" являющаяся юридическим лицом по законодательству Японии, именуемая в дальнейшем "Покупатель", заключили настоящий контракт о нижеследующем.

Предмет контракта.

Продавец изготовит и поставит Покупателю один образец монокристаллического сплава W-Ta диаметром 3,5 см и длиной 10 см, а Покупатель оплатит их изготовление и поставку.

Статья 1. Обязательства сторон.

1.1. Продавец изготовит в соответствии с Приложением, являющейся неотъемлемой частью настоящего контракта, 1 образец монокристаллического сплава W-Ta диаметром 3,5 см и длиной 10 см. 1.2. Продавец поставит Покупателю один образец монокристаллического сплава W-Ta через 120 дней с даты подписания контракта на условиях

1.3 Покупатель в течение 10 дней проведет приемку образца и сообщит о результатах Продавцу. В случае, если в течение этого срока не поступит каких-либо сообщений от Покупателя о дефектах, то образец из W-Ta считается принятым Покупателем.

1.4. Покупатель в течение 10 дней с даты поставки образца из W-Ta оплатит Продавцу поставку образца.

1.4. Сроки поставки. Датой поставки образца считается дата авианакладной в аэропорту

Статья 2. Цена контракта, порядок взаиморасчетов.

2.1. ~~Общая~~ цена контракта составляет 12.000 долларов США.

~~Цена за один образец составляет 12.000 долларов США.~~

2.2. В цену входят стоимость изготовления образца, упаковки, маркировки, транспортных расходов до аэропорта в г., страхования груза, оплата таможенных пошлин и таможенных услуг в г. Москве. Оплата таможенных пошлин и любых других платежей в США лежит на Покупателе.

2.3. Цена твердая и изменению не подлежит.

2.4. Банковские расходы на территории Российской Федерации несет Продавец, на территории США - Покупатель.

2.5. В случае задержки платежа Покупатель оплачивает пеню в размере 0.05% от суммы платежа за каждый день задержки, но не более 5% от суммы платежа.

2.6. В случае задержки поставки образца Продавцом, Покупатель имеет право удержать 0.05% от суммы платежа за каждый день задержки, но не более 5% от суммы платежа.

Статья 3. Упаковка, маркировка.

3.1. Образец должен быть упакован в тару, обеспечивающую его сохранность при транспортировке.

3.2. Маркировка должна быть выполнена несмываемой краской на английском языке и иметь следующую информацию:

Сделано в Российской Федерации

Изготовитель

Адрес изготовителя

Контракт N

Брутто

Нетто

Пункт назначения

Адрес и наименование грузополучателя

ORIGINAL PAGE IS
OF POOR QUALITY

В случае необходимости тара должна иметь специальную маркировку: "верх", "низ", "не кантовать", "осторожно".

Статья 4. Сдача и приемка товара (изделий).

Товар (изделие) считается поставленным Продавцом и принятым Покупателем:

- в отношении качества - при соответствии Требованиям, изложенным в Приложении,

- в отношении количества - в соответствии с количеством мест указанным в товарно-транспортной накладной.

После отгрузки товара Продавец сообщает Покупателю по телексу (факсу) об его отгрузке в течение 3-х дней с указанием номера рейса даты отгрузки.

Статья 5. Оплата.

Оплата товара (изделия), поставляемого по данному контракту должна быть произведена Покупателем, на счет Продавца, Beneficiary: Research Centre "Current Sources" (ISTOK), Podolsk, Russia, Account # 07003021/211 Bank of the beneficiary: Unicombank, Moscow, CHIPS UID 319546 (Unicombank (Podolsk): Komsomolskaya st., 46, Tel: 137-97-71) Via: Account # 04-095-713 with the Bankers Trust Company, PO BOX 318 Church Street Station, New York, 1008. Tel: (212) 250-25-00 Contact person: Virginia Rose, in Money Transfer Department.

Статья 6. Конфиденциальность.

6.1. Вся информация по конструкции технологии изготовления, условий эксплуатации и применения, переданная Продавцу в рамках настоящего контракта, должна рассматриваться как конфиденциальная. Продавец обязуется принять меры к сохранению указанной информации и не передавать её третьей стороне. Эти обязательства не относятся к информации из открытых источников.

6.2. Продавец обязан связать третью сторону, участвующую по необ-

ходимости в изготовлении или проверке образца по настоящему контракту, обязательствами, упомянутыми в этой главе.

Статья 7. Гарантии.

7.1. Гарантия Продавца на соответствие требованиям к образцу, изложенным в Приложении, действует в течение 12 месяцев, считая с даты поставки.

7.2. Если в течение гарантийного срока образец окажется не соответствующим спецификации, Продавец обязан заменить дефектное изделие за свой счет в течение 10 рабочих дней.

7.3. По просьбе Продавца и за его счет Покупатель должен вернуть дефектное изделие Продавцу.

7.4. Гарантии не распространяются на потери, связанные с небрежным обращением, неправильным хранением, использованием не по назначению.

Статья 8. Рекламация.

8.1. Претензии, касающиеся качества товара (изделия) могут быть предъявлены Покупателем Продавцу только, если качество товара (изделия) не соответствует требованиям к нему, оговоренным настоящим контрактом.

8.2. Претензии, касающиеся количества, могут быть предъявлены Покупателем Продавцу только в случае обнаружения недостачи внутри фирменной упаковки изготовителя, не носящей следов вскрытия.

8.3. Такого рода претензии излагаются письменно путем составления акта при участии представителя Продавца или, по согласованию с Продавцом, представителя нейтрального контролирующего органа страны Покупателя.

8.4. Покупатель имеет право предъявить претензии Продавцу в отношении качества в течение 10 дней с даты поставки.

По истечении вышеуказанного срока претензии не принимаются.

8.5. Претензии следует направить заказным письмом, с приложением всех необходимых документов подтверждающих прилагаемую претензию.

Вышеуказанное письмо должно содержать следующие атрибуты: номер

контракта и дату отправки документов, дату прибытия и инспектирования товара (изделия), количество товара (изделия), в чем конкретно выражается претензия. Продавец имеет право сам на месте проверить обоснованность предъявляемой претензии.

Статья 9. Форс-мажорные обстоятельства.

9.1. Стороны освобождаются от ответственности за частичное или полное невыполнение обязательств по настоящему контракту, если оно явилось следствием непреодолимой силы (стихийные бедствия, военные действия, забастовки, решения правительственных органов и т. д.), на которые стороны не могли повлиять разумными мерами.

9.2. Сторона, для которой создалась невозможность исполнения обязательств по контракту, обязана немедленно (но не позже 5 дней) информировать другую сторону о наступлении обстоятельств непреодолимой силы. При этом, сроки исполнения обязательств по контракту отодвигаются соразмерно времени, в течение которого действовали такие обстоятельства.

9.3. Доказательством наличия таких обстоятельств будут свидетельства соответствующих торговых палат обеих сторон.

9.4. Если эти обстоятельства будут длиться более 6 месяцев, то каждая сторона имеет право расторгнуть настоящий контракт, и, в этом случае, ни одна из сторон не вправе требовать от другой стороны возмещения каких-либо убытков.

Статья 10. Арбитраж.

В случае возникновения между сторонами споров и/или разногласий вне или в связи с действиями настоящего контракта, стороны предпримут все возможное для разрешения их путем переговоров.

Если стороны не придут к урегулированию споров и/или разногласий методом переговоров, эти споры и/или разногласия должны быть без каких-либо обращений в суд переданы для рассмотрения в Арбитраж, расположенный в г. Стокгольме, Швеция.

Разбирательство будет вестись следующим образом:

сторона намеревающаяся обратиться в Арбитраж, должна уведомить письменно другую о своих действиях, указав Ф.И.О. своего арбитра (которым может быть гражданин любой страны), его адрес, суть дела, а также номер и дату этого контракта.

По получении этого письма-уведомления другая сторона должна в течение 30 дней назвать своего арбитра (которым может быть гражданин любой страны) и сообщить первой стороне в письменном виде его Ф.И.О. и адрес.

Если стороне, обратившейся в Арбитраж, не удастся назвать арбитра в указанный срок, то в этом случае арбитра (которым может быть гражданин любой страны) назначается президентом торговой палаты г. Стокгольма, Швеция, в течение 30 дней после просьбы стороны, обратившейся в Арбитраж.

Назначенный арбитра не может быть отклонен сторонами участниками Арбитража. Двое арбитров могут назвать третьего арбитра (которым может быть гражданин любой страны) в течение 30 дней после их назначения.

Если арбитрам не удастся прийти к соглашению в отношении кандидатуры третьего арбитра, последний по просьбе сторон назначается президентом торговой палаты г. Стокгольма, Швеция. Назначенный арбитра не может быть отклонен сторонами.

Решение Арбитража принимается большинством голосов арбитров на основе и в рамках материалов настоящего контракта.

Решение должно быть мотивированным и кроме того содержать указания как должны быть поделены между сторонами расходы, связанные с их обращением в Арбитраж.

Решение Арбитражного Суда должно быть вынесено по возможности в течение 6 месяцев с даты начала заседания Арбитражного Суда, должно быть окончательным и обязательным к исполнению для обеих сторон.

Отношения сторон, которые не оговорены или не полностью оговорены настоящим контрактом, должны регулироваться принятыми нормами шведского международного права.

Применение правил конфликта по закону исключено.

Статья 11. Прочие условия.

11.1. Покупатель гарантирует сохранение прав собственности Продавца на материал образца и технологию его изготовления, а также на любую информацию передаваемую Покупателю и определяемую Продавцом как конфиденциальную. Ни одна из сторон не вправе передавать свои права и обязательства, предусмотренные настоящим контрактом, третьим лицам, за исключением законных правопреемников сторон, без письменного согласия другой стороны.

11.2. Настоящий контракт вступает в силу с момента подписания его сторонами и действует до полного выполнения обязательств сторонами. По соглашению сторон контракт может быть пролонгирован.

11.3. Действие контракта может быть прекращено в одностороннем порядке досрочно в случае невыполнения одной из сторон своих обязательств в течение 3 месяцев. При этом, виновная сторона обязана возместить другой стороне убытки. Под убытками понимаются только прямые расходы, косвенные убытки и упущенная выгода возмещению не подлежат.

11.4. После подписания настоящего контракта все ссылки на имевшие место ранее переговоры и переписку считаются недействительными.

11.5. Все изменения и дополнения к настоящему контракту будут иметь силу, если они совершены в письменной форме и подписаны уполномоченными представителями сторон.

11.6. Настоящий контракт составлен в 2-х экземплярах на русском и английском языках по одному экземпляру для каждой стороны, причем все экземпляры имеют одинаковую силу.

11.7. Настоящий контракт вместе с приложениями содержит 9 страниц.

Совершено в г. Москве Российская Федерация.....1993г.

Контракт вступает в силу с даты его подписания.

"_____" 199__г.

Николдв

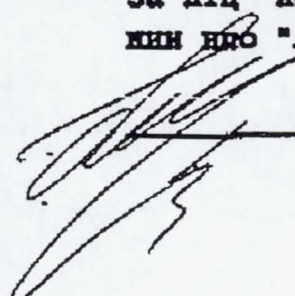
- 8 -

ПРИДІНЕСКІЕ АДРЕСА СТОРОН

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7-095-137-37-54**

**"SPACE EXPLORATION
ASSOCIATES"**

**За ИТЦ "ИСТОК"
НИИ ПРО "ЛУЧ"**



Ю.В.Николдв

**За "SPACE EXPLORATION
ASSOCIATES"**

Elliot B Kennel

16 February 1994

Contract No. N-108 K

The scientific-production association "Luch," being a legal entity according to the legislature of the Russian Federation, operating through its division - NTTs "Istok," henceforth named the "Seller," on the one hand, and the American association "Space Exploration Associates," being a legal entity according to the legislature of Japan, henceforth named the "Buyer," have entered into the said contract as described below.

Objective of the contract.

The Seller will fabricate and deliver to the Buyer a single specimen of a W-Ta monocrystalline alloy, 3.5 cm in diameter and 10 cm long, and the Buyer will pay for its fabrication and delivery.

Article 1. Obligations of the parties.

1.1. The Seller will fabricate in accordance with the Appendix, which is an inseparable part of said contract, one specimen of a monocrystalline W-Ta alloy, 3.5 cm in diameter and 10 cm long. The Seller will deliver to the Buyer one specimen of the monocrystalline W-Ta alloy within 120 days from the date of contract signature on the terms

1.3. The Buyer will within 10 days conduct an examination of the specimen and inform the Seller of the results. In the event that in the course of this time period no communication is received from the Buyer regarding defects, the W-Ta specimen will be considered as accepted by the Buyer.

1.4. The Buyer will within 10 days from the receipt of the W-Ta specimen pay the Seller for the delivery of the specimen.

1.4. Delivery date. The specimen delivery date will be considered as the date of the aviation bill of lading at the airport in the city of.

Article 2. Contract cost, sequence of interrelated calculations.

2.1. The total cost of the contract is US \$12,000.

The cost of a single specimen is US \$12,000.

2.2. The cost includes the cost of fabricating the specimen, packing, labeling, expenses for transportation to the airport in the city of , insurance charges, payment of customs duties and customs services in Moscow. Payment of customs duties and other payments in the USA are the Buyer's responsibility.

2.3. The cost is firm and not subject to change.

2.4. Bank expenses in the territory of the Russian Federation are born by the Seller, in US territory - by the Buyer.

2.5. In the event of a delay in payment, the Buyer will incur a cost of 0.05% of the payment sum for each day of delay, but not more than 5% of the payment sum.

2.6. In the event of a delay in receipt of the specimen by the Seller, the Buyer has the right to deduct 0.05% from the payment sum for each day of delay, but not more than 5% of the

payment sum.

Article 3. Packing and labeling.

3.1. The specimen must be packed in a packing that will protect it during transportation.

3.2. Labeling must be done with indelible dye in English and contain the following information:

Made in the Russian Federation

Manufacturer

Address of manufacturer

Contract No.

Gross weight

Net weight

Destination point

Address and name of freight recipient

If necessary, the package should have special markings: "top," "bottom," "do not tilt," "handle with care."

Article 4. Surrender and acceptance of merchandise (manufactured item).

The merchandise (manufactured item) is considered delivered by the Seller and accepted by the Buyer:

- in regard to quality - when in compliance with the Requirements as set forth in the Appendix,
- in regard to quantity - when in accordance with the quantity indicated on the merchandise transportation manifest.

After dispatch of the merchandise, the Seller will inform the Buyer via telex (fax) of its dispatch within the third day with specification of the dispatch route number.

Article 5. Payment.

Payment for the merchandise (manufactured item), supplied in accordance with said contract, must be made by the Buyer to the Seller's account, Beneficiary: Research Centre "Current Sources" (ISTOK), Podolsk, Russia, Account # 07003021/211.

Bank of the beneficiary: Unicombank, Moscow, CHIPS UID 319546 (Unicombank Podolsk: Komosmolskaya st. 46, Tel: 137-97-71).

Via: Account # 04-095-713 with Bankers Trust Company, PO Box 318 Church Street Station, New York, 1008.

Tel: (212) 250-2500

Contact person: Virginia Rose, in Money Transfer Department.

Article 6. Confidentiality.

6.1. All information on fabrication design technology, conditions of exploitation and application disclosed by the Seller within the framework of the said contract must be considered as proprietary. The Seller is obligated to take measures to protect the indicated information and not transmit it to a third party. These obligations do not pertain to information from open sources.

6.2. The Seller is obligated to bind a third party, which participates by necessity in the fabrication or in the examination of the specimen in accordance with the said contract, to the obligations mentioned in this Article.

Article 7. Warranties.

7.1. The Seller's warranty on the pertinent specimen requirements as stated in the Appendix will be in effect for 12 months from the delivery date.

7.2. If in the course of the warranty period the specimen is not found to be within specifications, the Seller is obligated to replace the defective part at his own expense within 10 working days.

7.3. At the Seller's request and at his expense the Buyer must return the defective part to the Seller.

7.4. The warranties do not extend to losses associated with carelessness, incorrect storage, unintended uses.

Article 8. Complaints.

8.1. Claims regarding the quality of the merchandise (manufactured part) can be presented by the Buyer to the Seller only if the quality of the merchandise (manufactured part) does not satisfy the requirements as stipulated in the said contract.

8.2. Claims regarding quantity can be presented by the Buyer to the Seller only in the event of the discovery of a shortage inside the manufacturer's package and with the package showing no evidence of previously having been opened.

8.3. These kinds of claims are to be in writing by drawing up a statement with the participation of a Seller's representative, or with the consent of the Seller, a representative of a neutral inspection organ in the Buyer's country.

8.4. The Buyer has the right to present claims to the Seller relative to quality within 10 days following the date of receipt. Claims will not be accepted after the expiration of the above stated time period.

8.5. Claims must be forwarded by registered letter with the inclusion of all necessary documentation to substantiate the enclosed claim.

The above mentioned letter must contain the following attributes: contract number and transmission date of documentation, date of arrival and inspection of the merchandise (manufactured part), quantity of merchandise (manufactured part), the specifics of the claim. The Seller has the right to do an on the spot check of the particulars of the claim presented.

Article 9. Force majeure circumstances.

9.1. The parties are relieved of responsibilities for partial or complete non-fulfillment of the terms of the said contract if due to insuperable forces (natural calamities, the effects of war, sabotage, decisions of governmental bodies, etc.), which the parties are unable to influence by reasonable means.

9.2. A party finding it impossible to discharge the responsibilities in accordance with the contract is obligated immediately (but no later than 5 days) to inform the other party of the advent of an insuperable force. Thereupon, the period of fulfillment of the contract responsibilities will be extended for a time proportional to the duration of such an insuperable force.

9.3. Proof of the existence of such circumstances will be attested to by appropriate chambers of commerce of both parties.

9.4. If these circumstances will last longer than 6 months, then each party has the right to cancel the said contract, and, in this case, neither of the parties has the right to demand any loss compensation from the other party.

Article 10. Arbitration.

In the event of disputes between the parties and/or discord beyond or in connection with the said contract, the parties will do everything possible to resolve them through negotiations.

If the parties fail to settle disputes and/or discords through negotiation, these disputes and/or discords must be submitted without any legal appeal for arbitration in Stockholm, Sweden.

The trial will be conducted in the following manner:

the party intending to turn to arbitration should notify the other in writing of his action by indicating the name of the arbitrator (who can be a citizen of any country), his address, date of action, and also the number and date of the said contract.

Upon receipt of this written notification the other party should within 30 days designate his arbitrator (who can be a citizen of any country) and inform the first party in letter form of his name and address.

If a party, having turned to arbitration, does not succeed in designating an arbitrator within the designated time period, then in this case the arbitrator (who can be a citizen of any country) will be designated by the president of the Chamber of Commerce in Stockholm, Sweden, during the 30 days following the request by the parties that are turning to Arbitration.

The designated arbitrator cannot be declined by the parties participating in Arbitration. The two arbitrators can designate a third arbitrator (who can be a citizen of any country) in the course of 30 days after their appointment.

If the arbitrators do not succeed in coming to agreement regarding the candidature of the third arbitrator, the latter is, by request of the parties, designated by the Chamber of Commerce in Stockholm, Sweden. The designated arbitrator cannot be declined by the parties.

The Arbitration decision is my majority vote of the arbitrators based on and within the framework of the materials of the said contract.

The decision must be justified and in addition contain instructions as to how the expenses associated with the Arbitration are to be divided between the parties.

The decision of the Arbitration Court must be rendered as far as possible within 6 months from the date the Arbitration

Court is seated. It should be final and obligatory for implementation by both parties.

The relationship of the party which is not stipulated or not entirely stipulated by the said contract should be governed by established common Swedish property law.

The application of the rule of conflict is in accordance with exclusivity law.

Article 11. Other conditions.

11.1. The Buyer guarantees the preservation of the property rights of the Seller to the specimen material and its fabrication technology, and also to any information transmitted to the Buyer and determined by the Seller to be proprietary. Neither of the parties has the right to turn over its rights and responsibilities as stipulated in the said contract to a third party, with the exception of legal representatives of the parties, without written agreement between both parties.

11.2. The said contract enters into force at the instant it is signed by the parties and remains in effect until the responsibilities of the parties are carried out. Contract extension can be made by agreement between the parties.

11.3. The operation of the contract can be terminated unilaterally ahead of schedule in the event one of the parties fails to discharge its responsibilities for a period of 3 months. In this event, the party at fault is obligated to recompense the other party for losses. Only actual expenses are considered as losses, there is no liability for indirect losses and loss of profit.

11.4. Upon signing of the said contract all references to previous negotiations and correspondence are considered null and void.

11.5. All changes and additions to the said contract will be in force if they are accomplished in written form and undersigned by the authorized representatives of the parties.

11.6. The said contract is drawn up in duplicate in the Russian and English languages with one copy to each party, each copy having equal validity.

11.7. The said contract together with the Appendix contain 9 pages.

Accomplished in Moscow, the Russian Federation, 1993.

The contract becomes effective on the date of signing.

_____ 199__.

Page 8 lists the Legal Addresses of the Parties and is self-explanatory.

The Russian signer on behalf of NTTs "ISTOK" and NII NPO "Luch" is Yu. V. Nikolayev.

APPENDIX

TECHNICAL REQUIREMENTS on the monocrystalline specimen of W-Ta alloy

1. Content in the alloy of the alloying component Ta: 1.5 ± 0.2 % by wt.

2. Possible orientation of the monocrystal: $\langle 110 \rangle$. The allowable deviation from the axis of orientation is up to 5° .

3. The content of basic impurities in the alloy does not exceed:
(in % by wt.)

Material	C	O	N	Me
W-Ta	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-3}$	$\sim 1 \cdot 10^{-4}$	$\sim 1 \cdot 10^{-1}$

4. The allowable angle of mutual disorientation of the subgrain is up to 4° .

5. Deviation in specimen dimensions : diameter - 3.5 ± 0.1 cm
length - 10.0 ± 0.2 cm

REPORT DOCUMENTATION PAGE

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6. AUTHOR(S) Elliot B. Kennel, Alexey Nikolayevich Ivanov, and Yuri Vyacheslavovich Nikolayev					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Space Exploration Associates 141 W. Xenia Avenue PO Box 579 Cedarville, Ohio 45314				8. PERFORMING ORGANIZATION REPORT NUMBER E-9199	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA CR-195397	
11. SUPPLEMENTARY NOTES Project Manager, John M. Sankovic, Space Propulsion Technology Division, organization code 5330, NASA Lewis Research Center, (216) 977-7429.					
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13. ABSTRACT (Maximum 200 words) This effort sought to exploit advanced single crystal tungsten-tantalum alloy material for fabrication of a high strength, high temperature arcjet anode. The use of this material is expected to result in improved strength, temperature resistance and lifetime compared to state of the art polycrystalline alloys. In addition, the use of high electrical and thermal conductivity carbon-carbon composites was considered, and is believed to be a feasible approach. Highly conductive carbon-carbon composite anode capability represents enabling technology for rotating-arc designs derived from the Russian Scientific Research Institute of Thermal Processes (NIITP) because of high heat fluxes at the anode surface. However, for US designs the anode heat flux is much smaller, and thus the benefits are not as great as in the case of NIITP-derived designs. Still, it does appear that the tensile properties of carbon-carbon can be even better than those of single crystal tungsten alloys, especially when nearly-single-crystal fibers such as Vapor Grown Carbon Fiber (VGCF) are used. Composites fabricated from such materials must be coated with a refractory carbide coating in order to ensure compatibility with high temperature hydrogen. Fabrication of tungsten alloy single crystals in the sizes required for fabrication of an arcjet anode has been shown to be feasible. Test data indicate that the material can be expected to be at least the equal of W-Re-HfC polycrystalline alloy in terms of its tensile properties, and possibly superior. We are also informed by our colleagues at Scientific Production Association Luch (NPO Luch) that is possible to use Russian technology to fabricate polycrystalline W-Re-HfC or other high strength alloys if desired. This is important because existing engines must rely on previously accumulated stocks of these materials, and a fabrication capability for future requirements is not assured.					
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